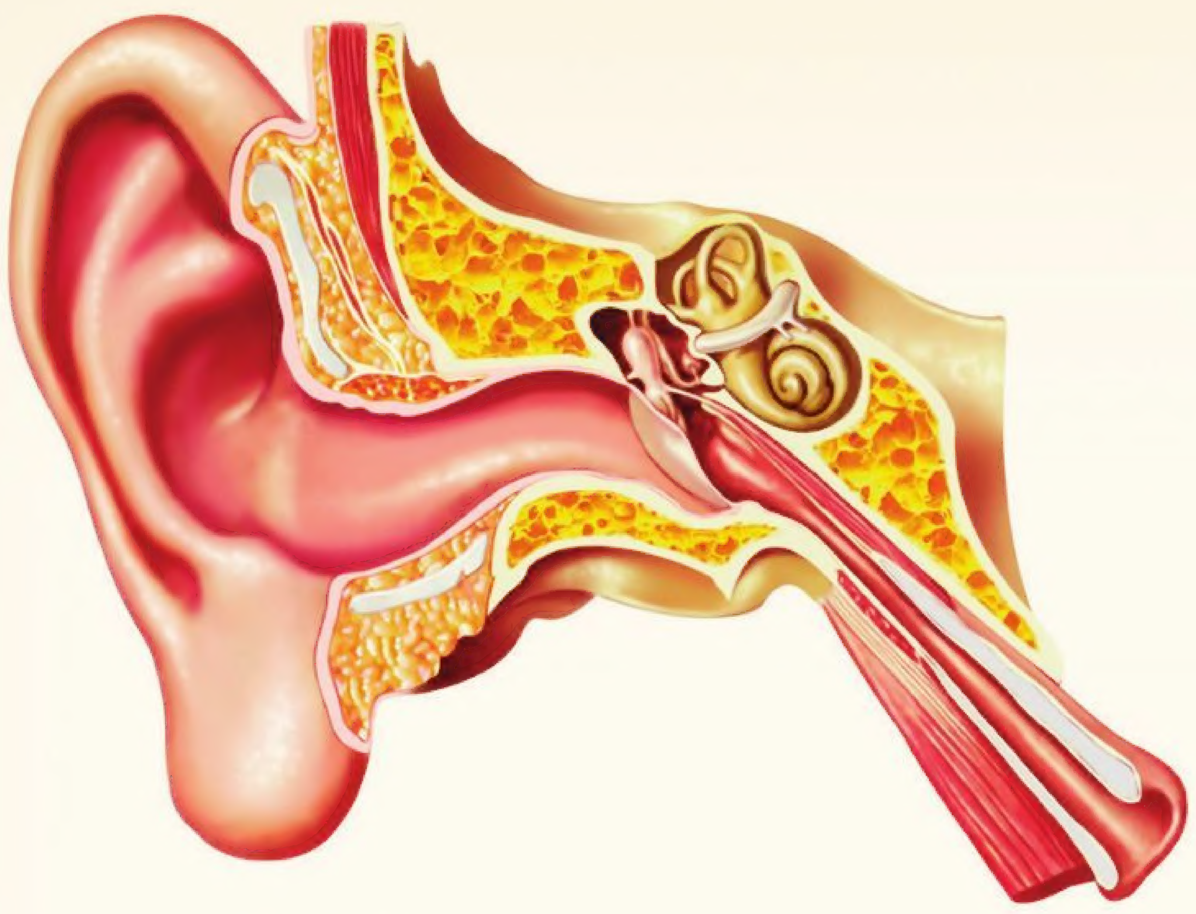
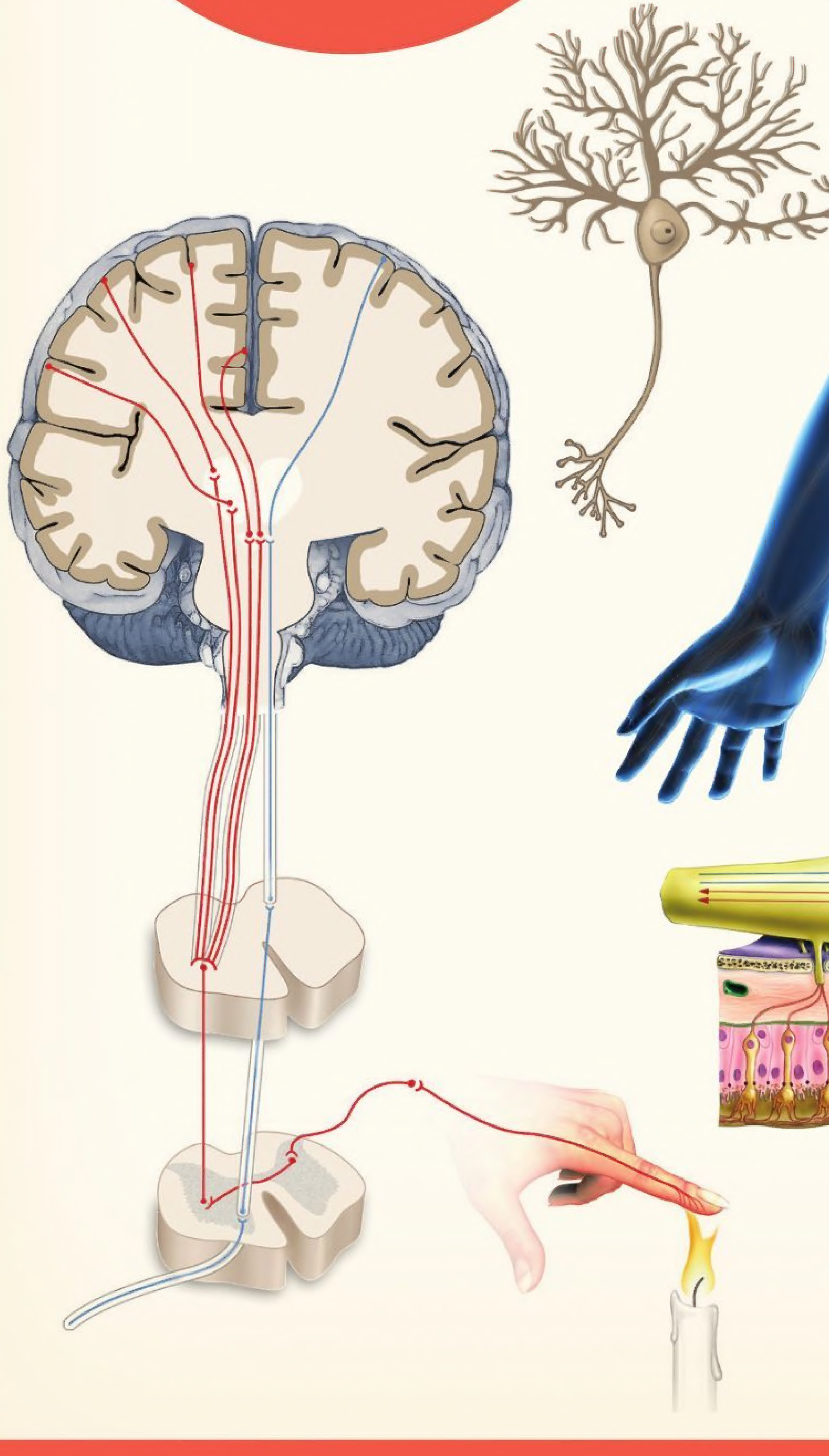


HOW IT WORKS BOOK OF THE SENSES

PART OF THE **HUMAN BODY** SERIES



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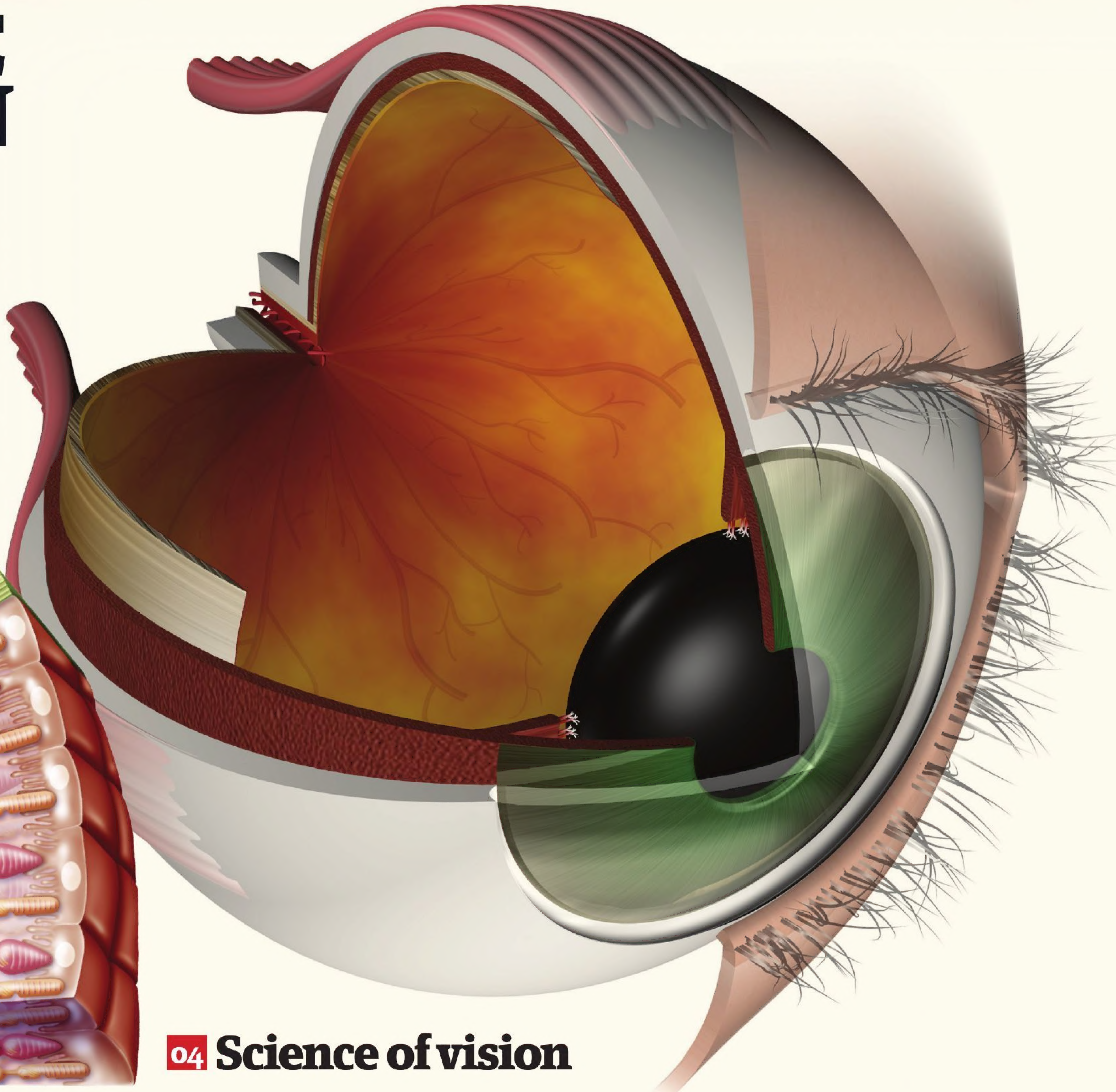

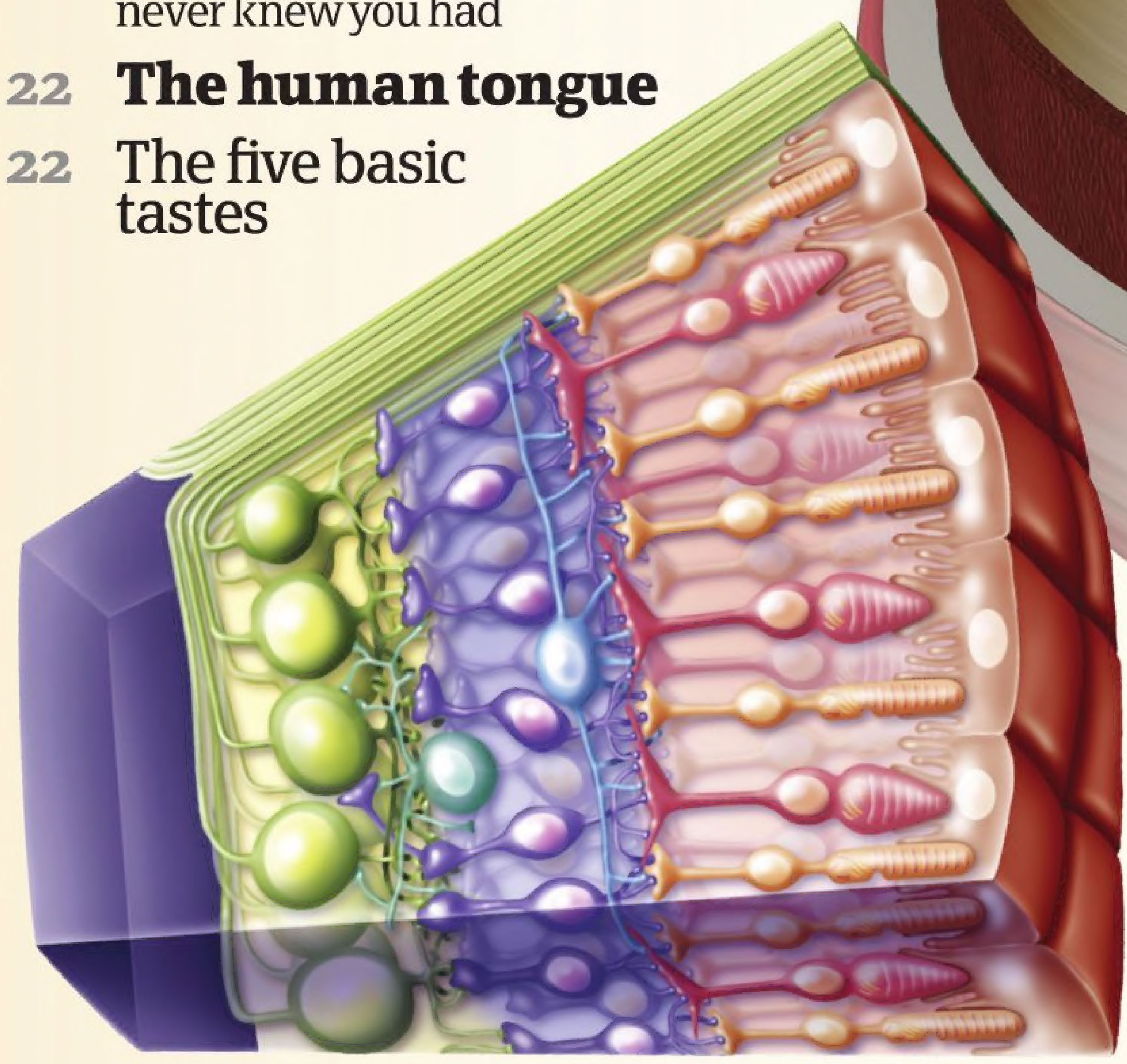

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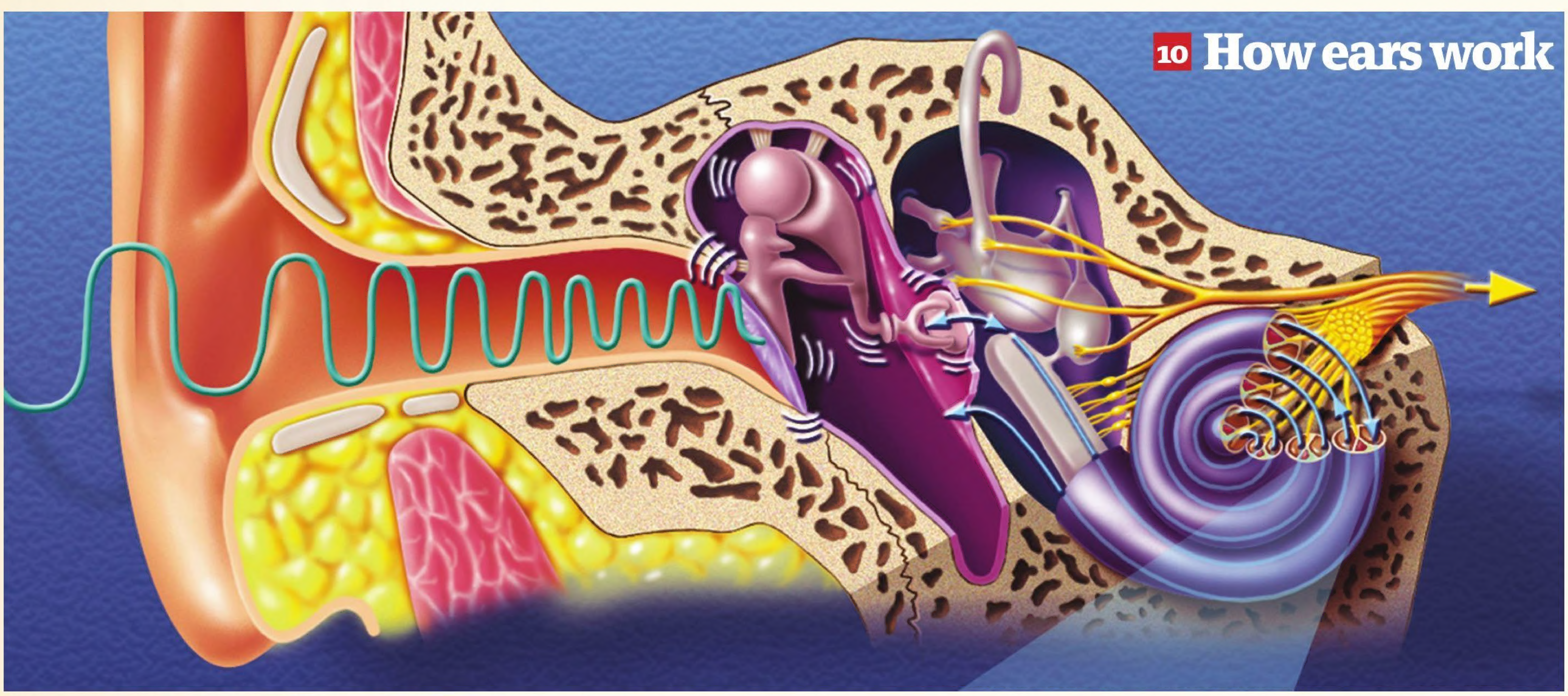

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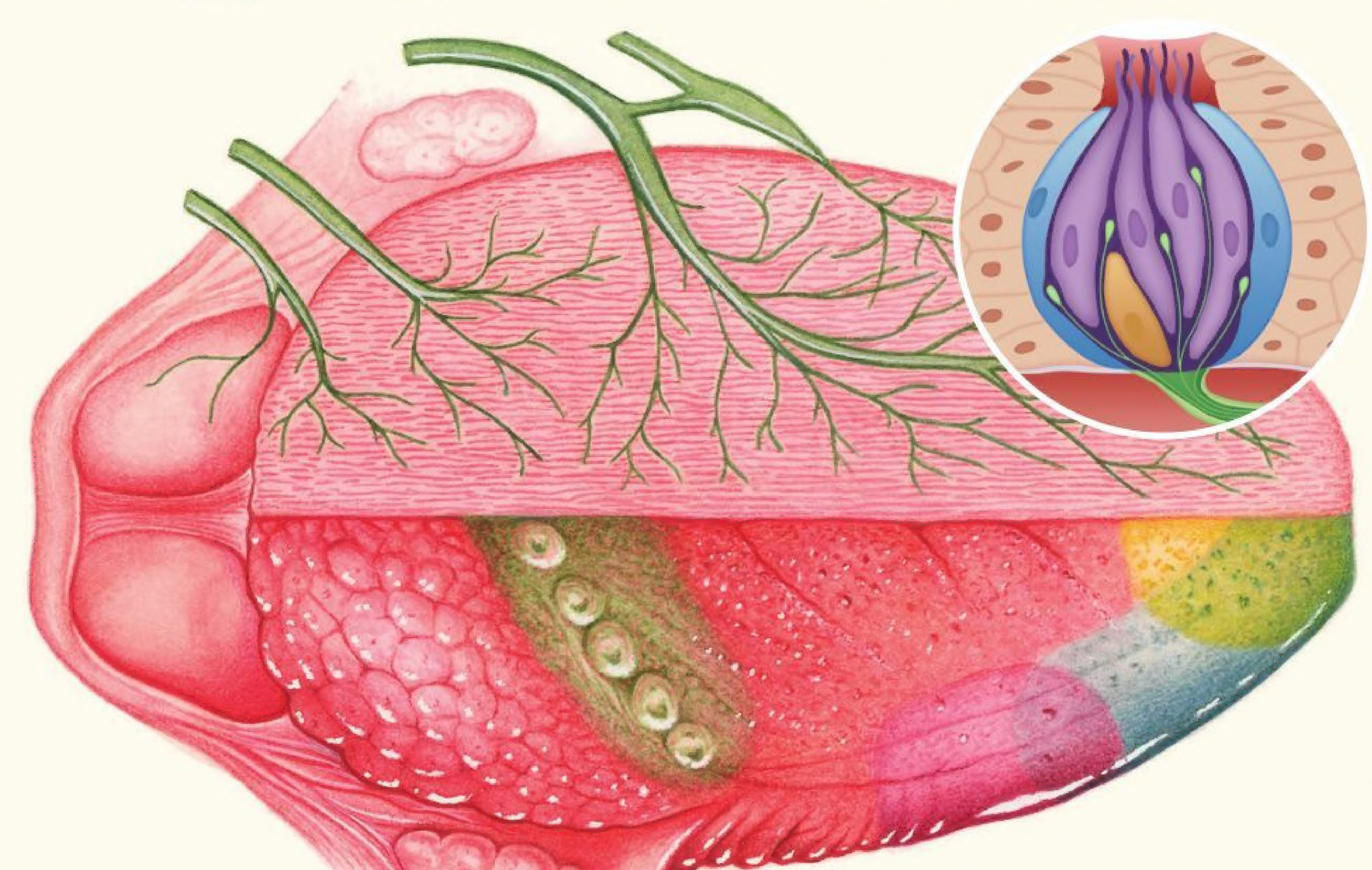

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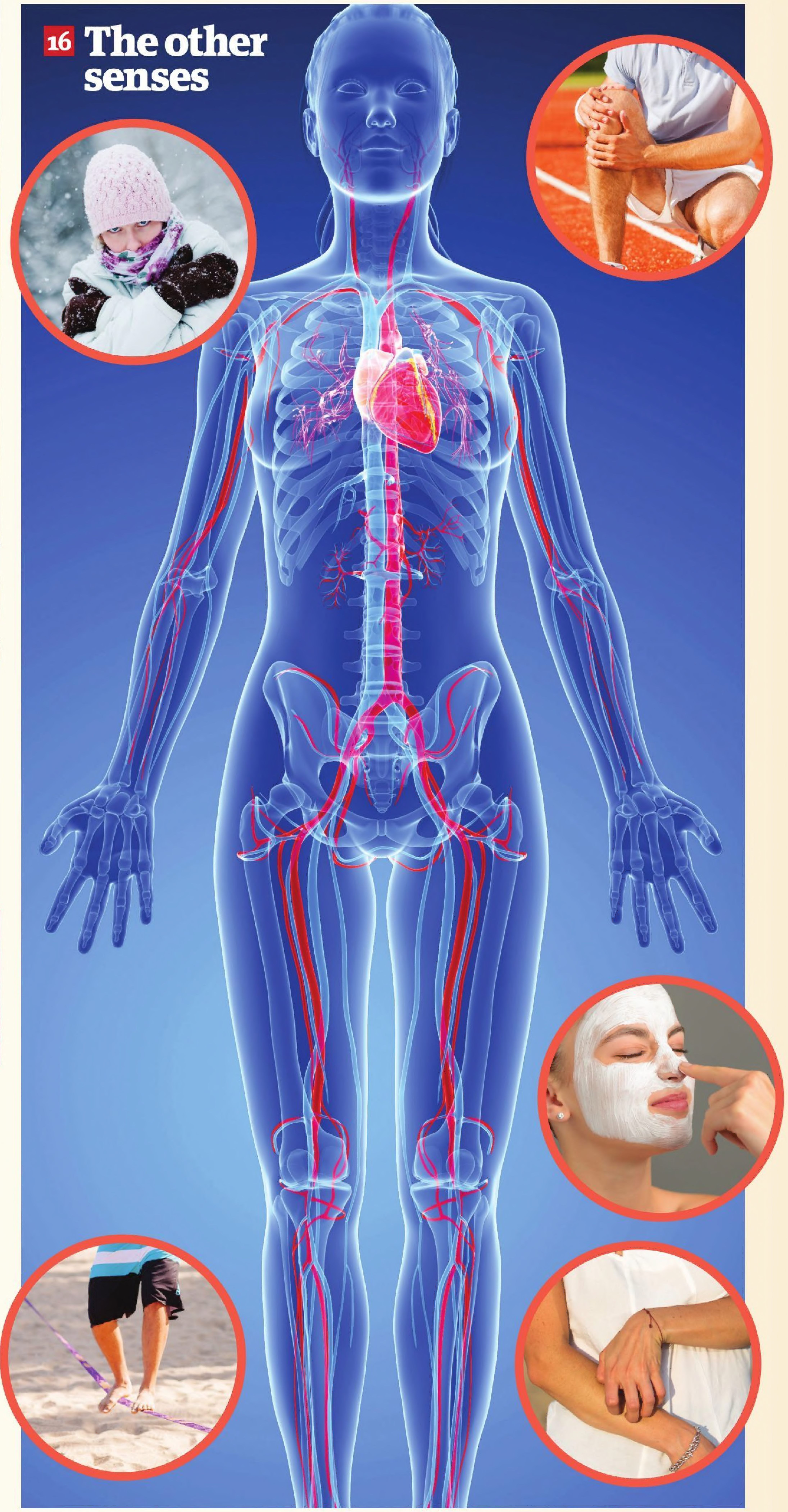


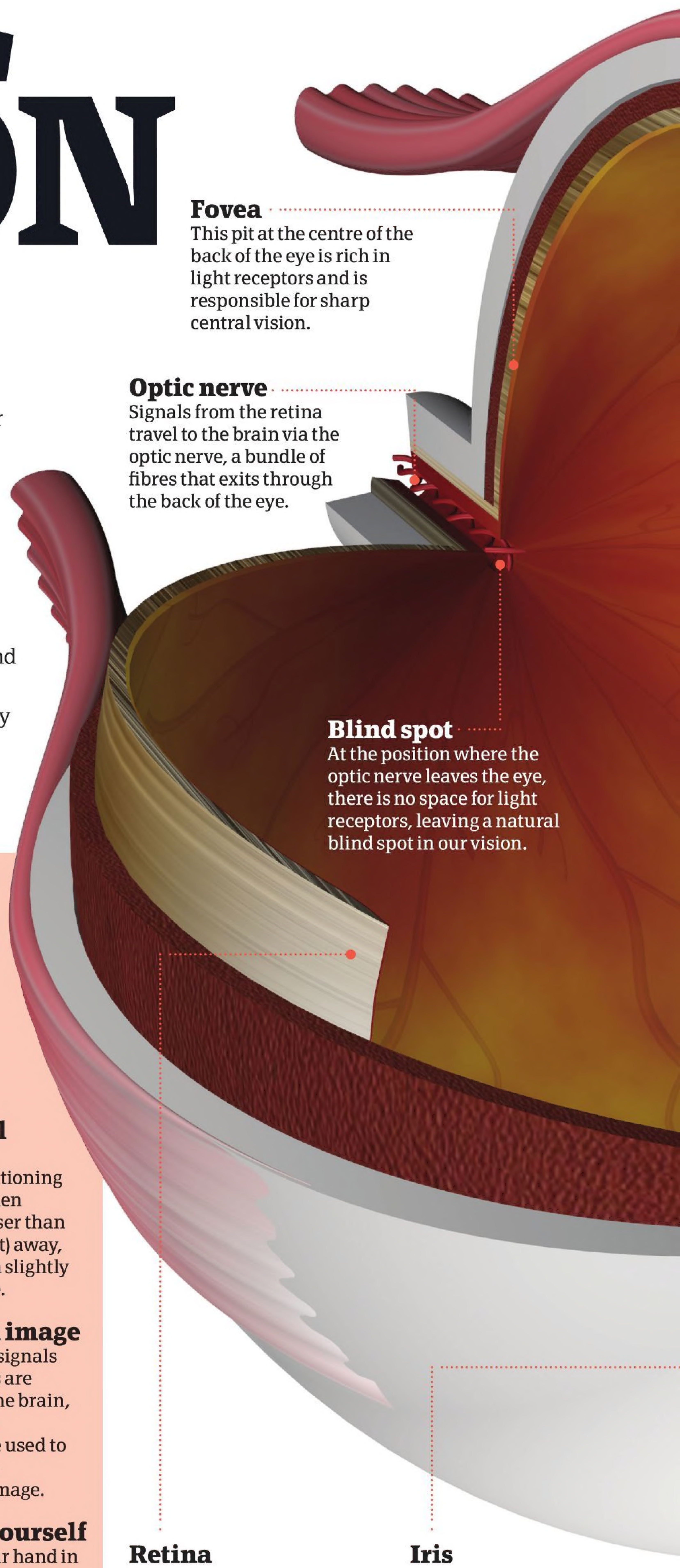
SCIENCE OF VISION

Uncovering one of the most complex constructs in the natural world

The structure of the human eye is so complex that it's hard to believe that it's not the product of intelligent design, but by looking at the eyes of other animals, scientists have shown that it evolved very gradually from a simple light-dark sensor over the course of around 100 million years. It functions in a very similar way to a camera, with an opening through which the light enters, a lens for focusing and a light-sensitive membrane at the back.

The amount of light that enters the eye is controlled by the circular and radial muscles in the iris, which contract and relax to alter the size of the pupil. The light first passes through a tough protective sheet called the cornea, and then moves into the lens. This adjustable structure bends the light, focusing it down to a point on the retina, at the back of the eye.

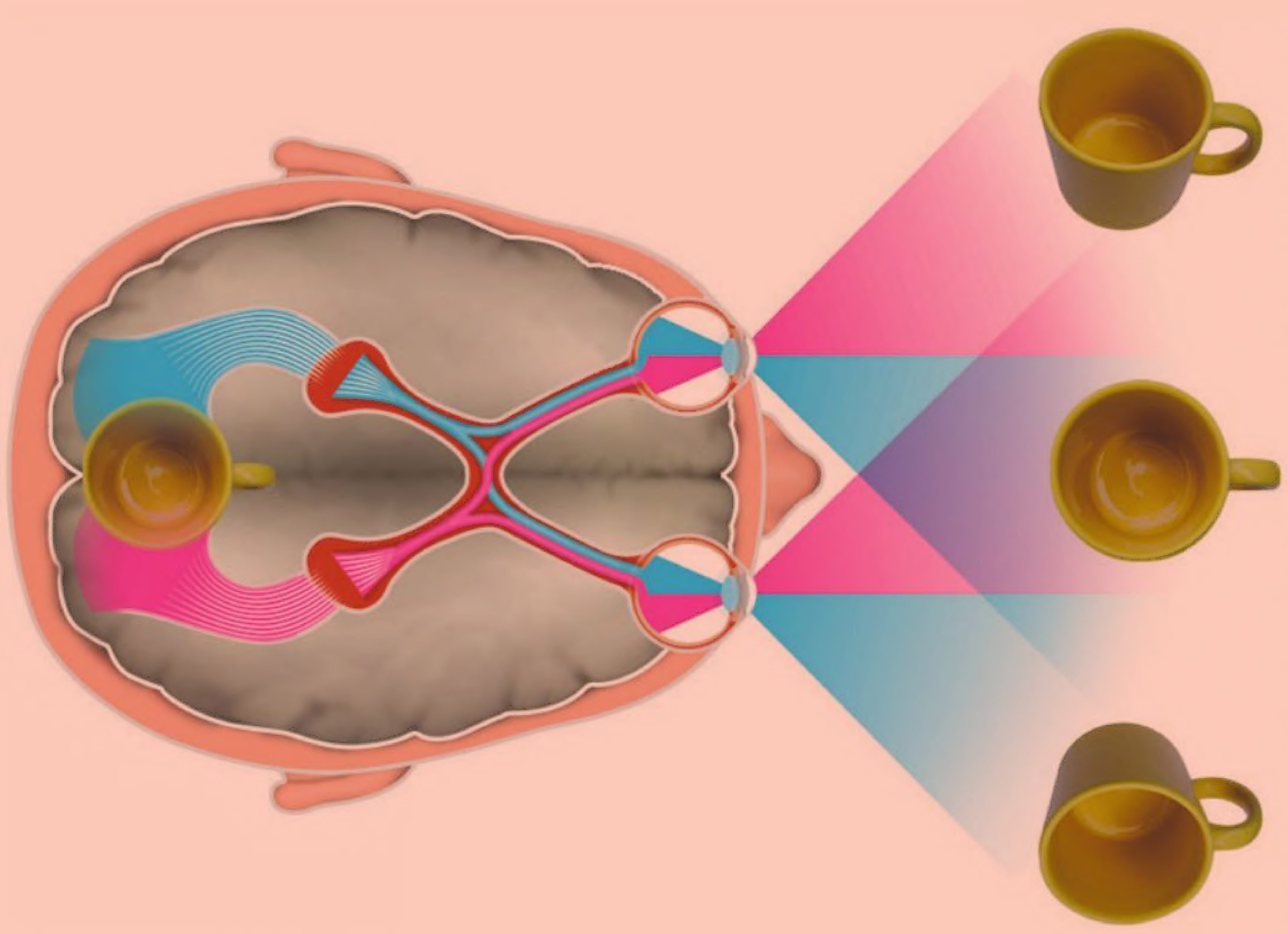
The retina is covered in millions of light-sensitive receptors known as rods and cones. Each receptor contains pigment molecules, which change shape when they are hit by light, triggering an electrical message that travels to the brain via the optic nerve.



Seeing in three dimensions

Each eye sees a slightly different image, allowing the brain to perceive depth

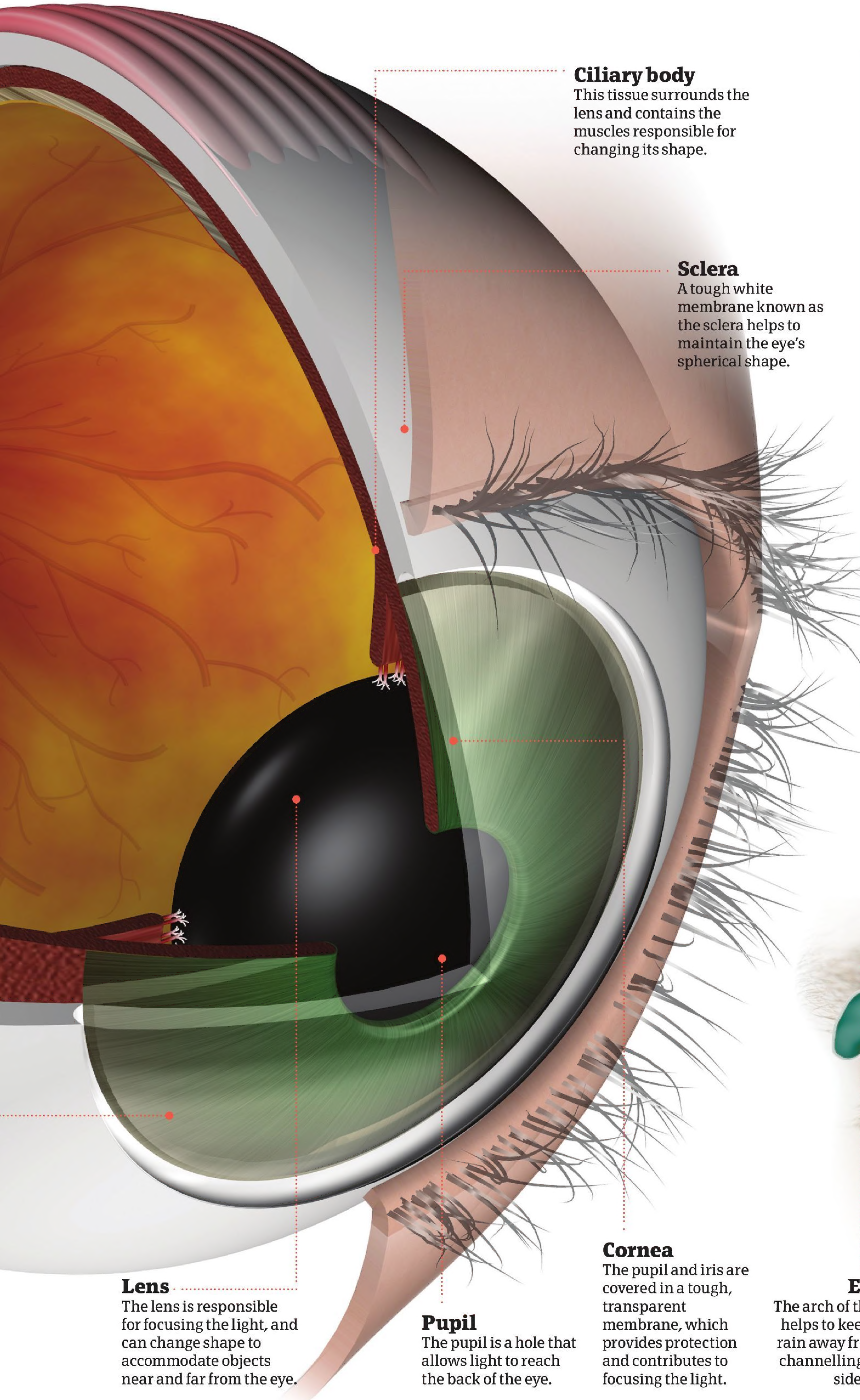
Our eyes are only able to produce two-dimensional images, but with some clever processing, the brain is able to build these flat pictures into a three-dimensional view. Our eyes are positioned about five centimetres (two inches) apart, so each sees the world from a slightly different angle. The brain compares the two pictures, using the differences to create the illusion of depth.



Individual image
Due to the positioning of our eyes, when objects are closer than about 5.5m (18ft) away, each eye sees a slightly different angle.

Combined image
The incoming signals from both eyes are compared in the brain, and the subtle differences are used to create a three-dimensional image.

Try it for yourself
By holding your hand in front of your face and closing one eye at a time, it is easy to see the different 2D views perceived by each eye.

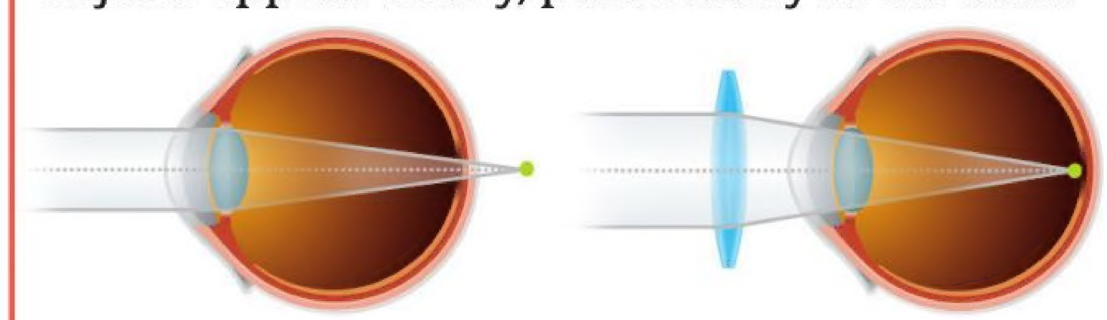


Vision problems

The most common problems with our eyesight

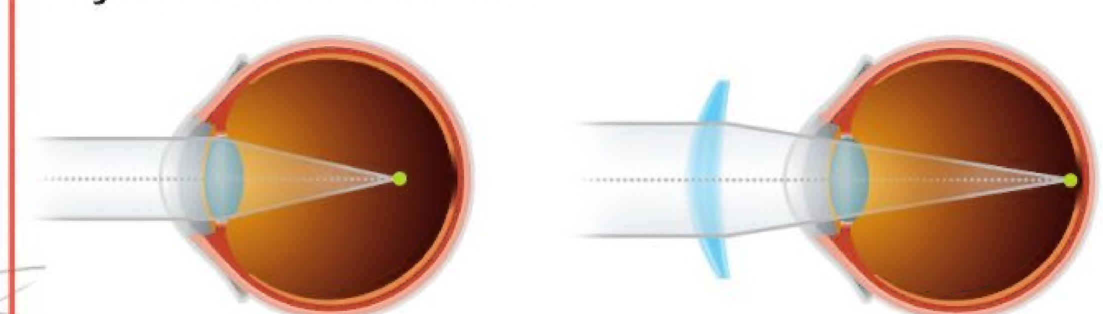
Farsightedness (hyperopia)

If the eye is too short, the cornea is too flat, or if the lens sits too far back, incoming light is focused behind the retina, making nearby objects appear blurry, particularly in the dark.



Nearsightedness (myopia)

If the eye is too long, or the cornea and lens are too curved, the light is focused before it hits the back of the eye, and then starts to defocus again as it reaches the retina, making distant objects difficult to see.

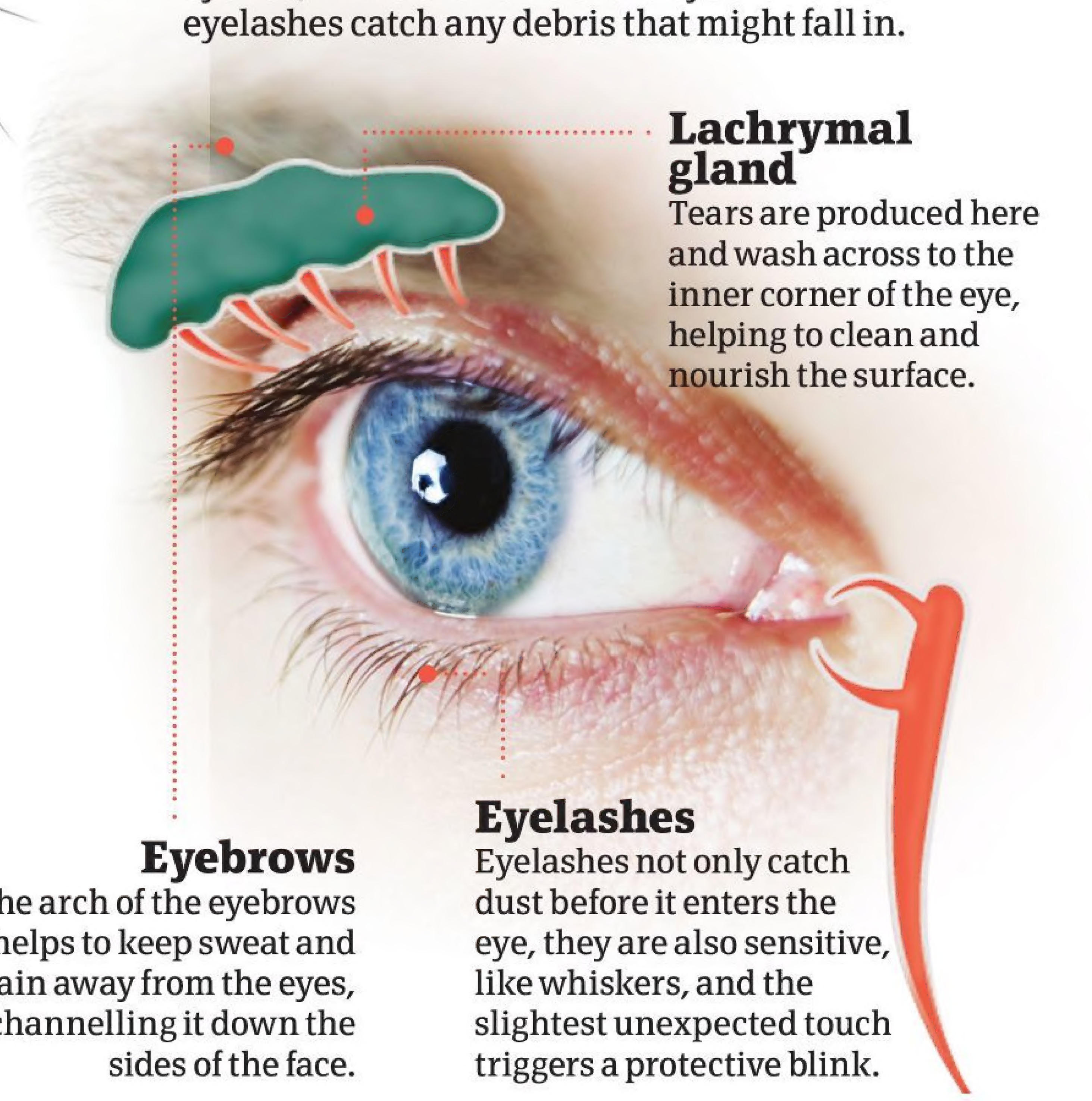


Colour-blindness

This rare condition is often linked to a gene on the X-chromosome and occurs more commonly in men than in women. A defect in the cone cells of the eye reduces the number of colours that can be detected.

Protection

The eyes are shielded by several layers of protection. They are almost completely encased in bone at the back and insulated from shock by layers of muscle and connective tissue. The front is kept moist with tears and constantly wiped by the eyelids, while the hairs of the eyebrows and eyelashes catch any debris that might fall in.



Colour vision

Why humans see the world in so many colours

Night monkeys have large eyes that enhance their nocturnal vision

Open your eyes, and you are met with an array of different colours, but amazingly you can only detect three different wavelengths of light, corresponding to green, blue, and red. Combining these three signals in the brain creates millions of different shades.

Each eye has between 6 and 7 million cone cells, containing one of three colour-sensitive proteins known as opsins. When photons of light hit the opsins, they change shape, triggering a cascade that produces electrical signals, which in turn transmit the messages to the brain. Well over half of our cone cells respond to red light, around a third to green light, and just two per cent to blue light, giving us vision focused around the yellow-green region of the spectrum.

The vast majority of the cone cells in the human eye are located in the centre of the retina, on a spot known as the fovea, measuring just fractions of a millimetre across. Light is focused on this point, providing a crisp, full-colour image at the centre of our vision. The remainder of the retina is dominated by 120 million rod cells, which detect light, but not colour.

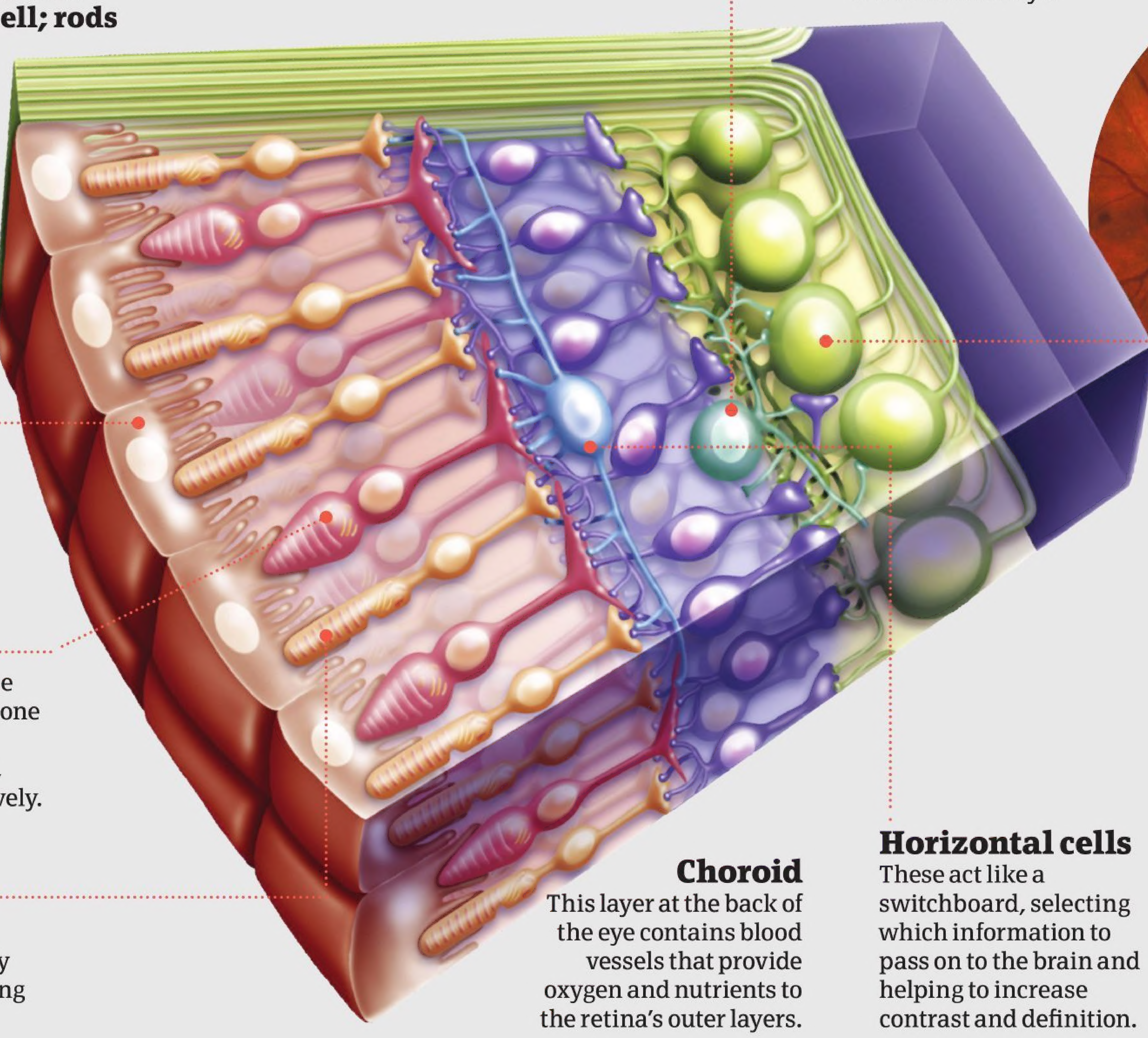
We are so used to seeing the world in red, green and blue that it might seem strange to think that most other animals cannot, but three-coloured vision like our own is relatively unusual. Some species of fish, reptiles and birds have four-colour vision, able to see red, green, blue and ultraviolet or infrared light, but during mammalian evolution, two of the four cone types were lost, leaving most modern mammals with dichromatic vision – seeing in shades of just yellow and blue.

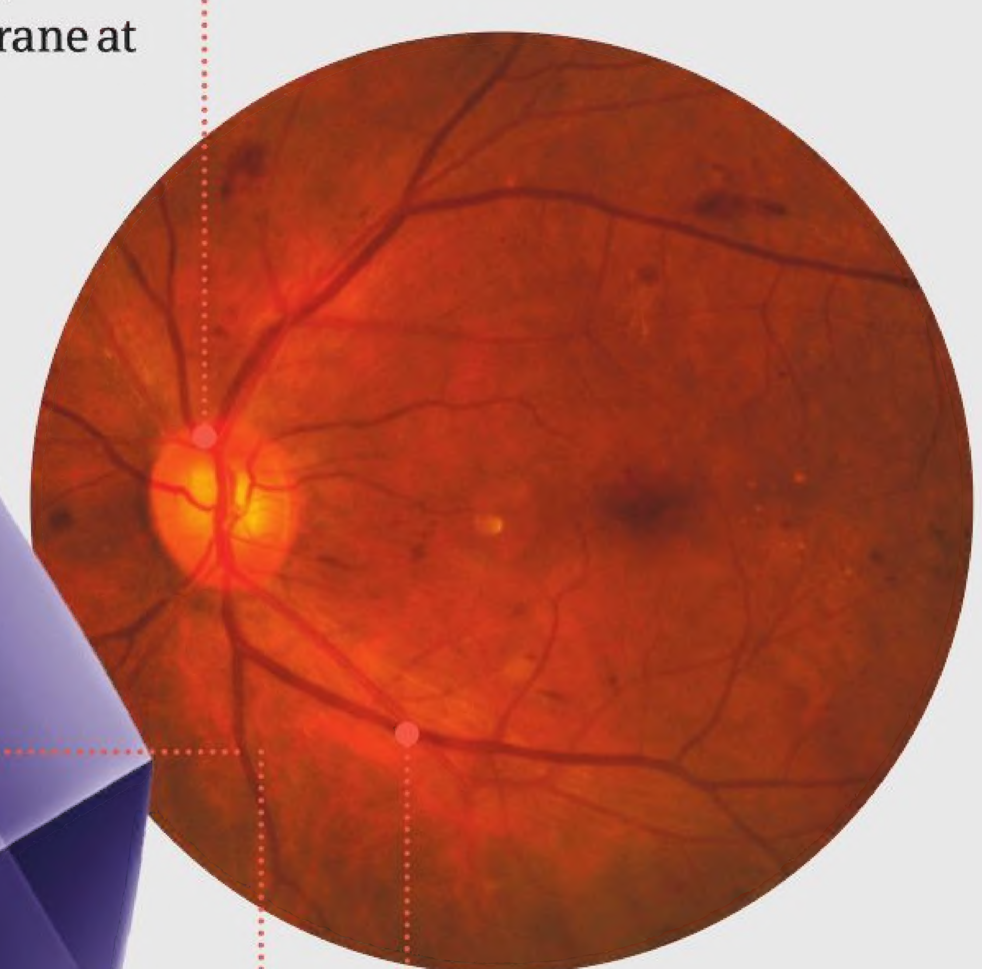
This was not a problem for many early mammals, because they were largely nocturnal, and lived underground, where there was little need for good colour vision. However, when primates started moving into the trees, a gene duplication gave some species the ability to see red, providing a significant evolutionary advantage in picking out ripe red fruit against the green leaves.

Even today, not all primates can see in three colours; some have dichromatic vision, and many nocturnal monkeys only see in black and white. It is all down to environment; if you don't need to see all of the colours in order to survive, then why waste energy making the pigments?

Light and colour

As light hits the back of the eye, it interacts with two different types of cell; rods and cones





Amacrine and bipolar cells
These cells transfer information from the rods and cones to the ganglion cells.

Retina
Light is detected by a multilayered membrane at the back of the eye.

Sclera
The white part of the eye continues all the way to the back of the retina, providing structural support.

Pigment epithelium
This dense sheet of cells contains dark pigment granules, which absorb excess light, preventing it from scattering inside the eye.

Cone cell
The human eye has three types of light-sensitive cone cell, each for a different wavelength of light, red, green and blue respectively.

Rod cell
Rod cells cannot detect colour, but are extremely sensitive to light, allowing us to see in the dark.

Choroid
This layer at the back of the eye contains blood vessels that provide oxygen and nutrients to the retina's outer layers.

Horizontal cells
These act like a switchboard, selecting which information to pass on to the brain and helping to increase contrast and definition.

Ganglion cells
The ganglion cells are neurones, and are responsible for transmitting incoming visual signals to the brain.

Blood vessels
The retina's inner layers receive their nutrients from a network of blood vessels on the inside of the eye.

How we see

Look around you – do you know what you're seeing with?

The back of the eye is covered in a layer of light-sensitive cells measuring just fractions of a millimetre in thickness. When photons of light hit the pigments inside the cells, it triggers a cascade of signals, which pass through a series of different connections before they are transmitted to the brain.

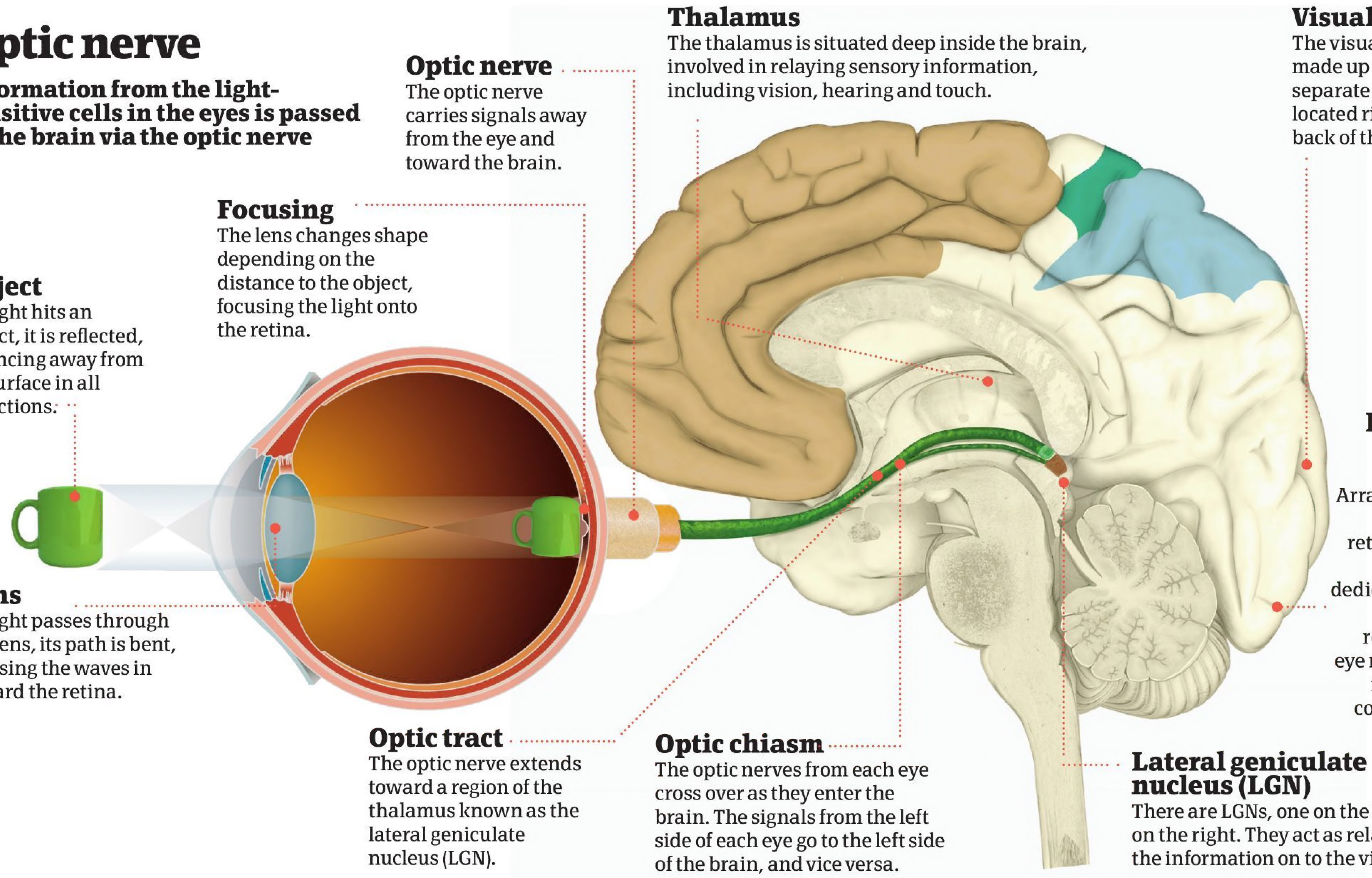
First, they move through interneurones and then to neurones known as ganglion cells. These cells are cross-linked, able to compare adjacent signals, filtering out some of the information before passing it on to the brain. This helps to improve contrast and definition. The neurones travel across the back surface toward the optic nerve, which relays the information into the brain.

As the two optic nerves enter the brain, they cross over, coming together at a point known as the optic chiasm. Here, signals from the left side of both eyes are diverted to the left side of the brain, and vice versa, allowing the images from both eyes to be combined and compared.

The signals enter the brain via the thalamus, which separates the incoming information into two parts, one containing colour and detail, and the other movement and contrast. The messages then move to the back of the brain, and into the visual cortex. The cortex is laid out so that it mirrors the back of the retina, allowing a detailed image to be reconstructed.

Optic nerve

Information from the light-sensitive cells in the eyes is passed to the brain via the optic nerve



Object
As light hits an object, it is reflected, bouncing away from its surface in all directions.

Focusing
The lens changes shape depending on the distance to the object, focusing the light onto the retina.

Optic nerve
The optic nerve carries signals away from the eye and toward the brain.

Thalamus
The thalamus is situated deep inside the brain, involved in relaying sensory information, including vision, hearing and touch.

Visual cortex
The visual cortex made up of six separate parts, located right at the back of the brain.

Primary visual cortex
Arranged like a map of the retina, it has a large area dedicated to the fovea – the region of the eye responsible for detailed colour vision.

Lens
As light passes through the lens, its path is bent, focusing the waves in toward the retina.

Optic tract
The optic nerve extends toward a region of the thalamus known as the lateral geniculate nucleus (LGN).

Optic chiasm
The optic nerves from each eye cross over as they enter the brain. The signals from the left side of each eye go to the left side of the brain, and vice versa.

Lateral geniculate nucleus (LGN)
There are LGNs, one on the left, and one on the right. They act as relays and send the information on to the visual cortex.

Quick-fire questions

Why do we see in black and white at night?
The colour-sensitive cone cells in the eye function like slow camera film – they produce highly detailed images, but require lots of light to work. In contrast, light-sensitive rod cells are like fast film. They respond to low levels of light, but cannot detect colour, producing a grainy, black-and-white image.

Why does our eyesight get worse as we get older?
As the eye ages, the lens becomes less flexible, making it increasingly difficult to focus on nearby objects. Luckily, this is easily corrected with glasses. Cloudy areas, known as cataracts, can also start to appear within the lens, making vision appear blurred or misty, but this can often be fixed with simple surgery.

Why do our eyes jump instead of moving around smoothly?
Movement of the eye is controlled by the brainstem. Our vision would be blurry if our eyes moved smoothly, so they jump in steps known as saccades. The brain stitches the images together, like the frames in a film, producing the illusion of continuous movement.

Why do some animals have their eyes on the sides of their head?
Forward-facing eyes are incredibly useful for primates, who need to be able to accurately judge depth when jumping between trees, for example, and for predators who need to pinpoint their prey. In contrast, prey animals need to be able to watch for danger, and often sacrifice binocular vision for a more rounded view of their environment.

How animals see the world

Take a look at the world through a different set of eyes

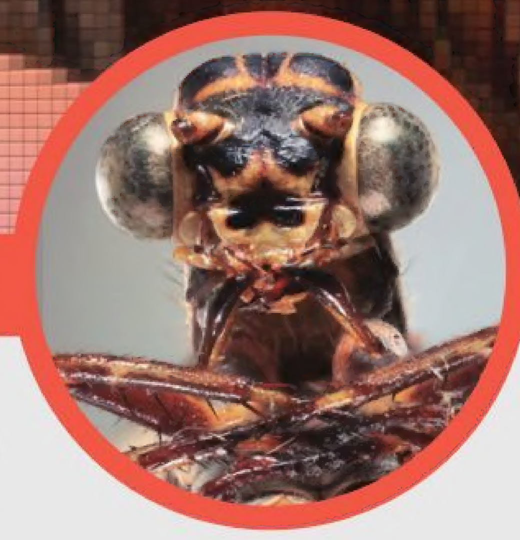
Each panel shows how each animal would see this picture

DOG

For a long time, it was thought dogs saw the world in black and white, distinguishing between objects only based on differences in light and contrast. It is now known that they have two-colour vision, seeing the world in shades of yellow and blue. Dogs have good night vision and the back of their eye contains a reflective layer known as tapetum, which helps to maximise light detection in the dark. However, the central part of their retina is only 20 per cent cone cells (compared to 100 per cent in humans), so although they see better in low light, their daytime vision is much less detailed than our own.

BIRD

Birds have arguably the most advanced vision in the animal kingdom. Rather than seeing in three colours, most birds can see four, extending their visual range into the ultraviolet part of the spectrum. Each of their cone cells also contains a drop of oil, which acts as a filter, further increasing their visual acuity. Why birds evolved the ability to see ultraviolet light is unclear. Some have UV-reflective feathers, others use their keen eyesight to spot UV-bright moths, butterflies, and fruits, and birds of prey use their UV vision to track rodents, picking up on their bright urine trails among the dense vegetation in the fields.



INSECT

Insects are so small that if they had eyes like ours, the tiny lens would be unable to bend and focus the light. Instead, they have compound eyes, built from many smaller units known as ommatidia. Each has its own lens, a crystalline cone, pigments and light-sensitive cells, and together they create a mosaic, similar to the pixels on a television screen. The more ommatidia an insect has, the higher the resolution of the image. Some insects, like dragonflies, have around 50,000 of these units, giving them a clear view of the world around them, allowing them to rapidly detect movement in their environment.

ABOVE The original image from below, with a colour spectrum as seen by humans

SNAKE

Pythons, boas and pit vipers have eyes surprisingly similar to our own, but they are able to see something we can't. Using specialist pit organs near their noses, these snakes can 'see' heat. The pits have a pinhole opening and at the bottom is a membrane similar to the retina, with a tightly packed network of heat-sensitive neurones – between 500 and 1,500 cells per square millimetre. The signals from the eyes and the pits converge on the same point in the brain, allowing the snakes to produce a combined visual and thermal image, or to switch between the two, like putting on a pair of night-vision goggles.

RAT

Rats are much more responsive to changes in brightness than colour, and they were originally thought to be colour-blind – 99 per cent of the light-sensitive cells in their eyes are rods. However, it is now known that they are able to detect some colour. Most (88 per cent) of their cone cells are sensitive to green light, but the remainder allow them to detect light in the blue-ultraviolet end of the spectrum. This ability allows the rodents to see territorial urine marks left by other animals. Because they rely on rod cells to see, their visual acuity is low and their vision is much blurrier than our own.

HORSE

Horses have their eyes on the sides of their head, so they have a much wider field of view that we do. However, they cannot see directly in front of themselves at close range and have a triangular blind spot that extends about 1.2 metres (4 feet) in front of their faces. At longer distances, the horse can use both eyes together for binocular vision, but they are also able to use each eye separately. With one eye looking forward and one looking back, they can keep a careful watch for potential danger. Like most other mammals, they cannot see red, so their world is a combination of shades of yellow, blue, green and grey.

How ears work

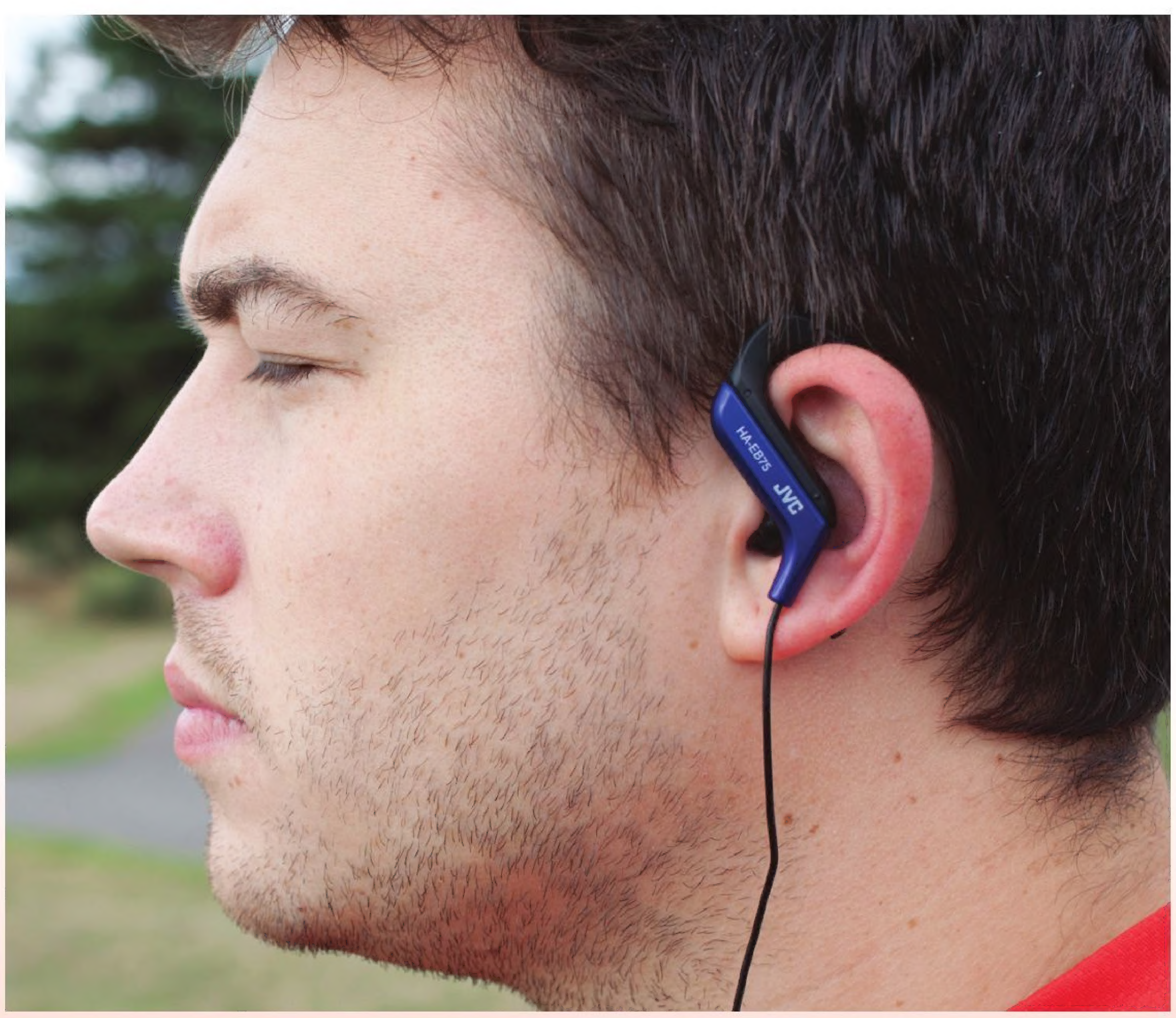
The human ear performs a range of functions, sending messages to the brain when a sound is made while also providing your body with a sense of balance

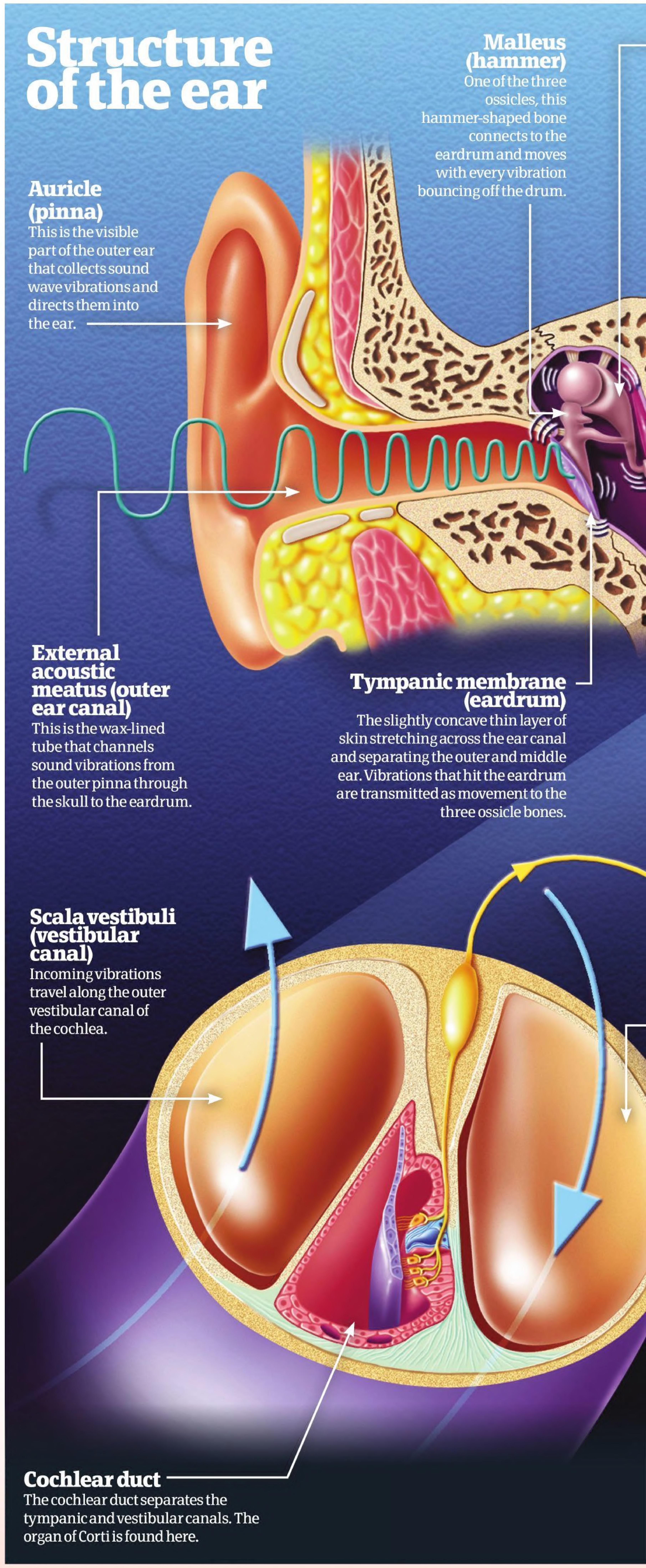
The thing to remember when learning about the human ear is that sound is all about movement. When someone speaks or bangs a drum or makes any kind of movement, the air around them is disturbed, creating a sound wave of alternating high and low frequency. These waves are detected by the ear and interpreted by the brain as words, tunes or sounds.

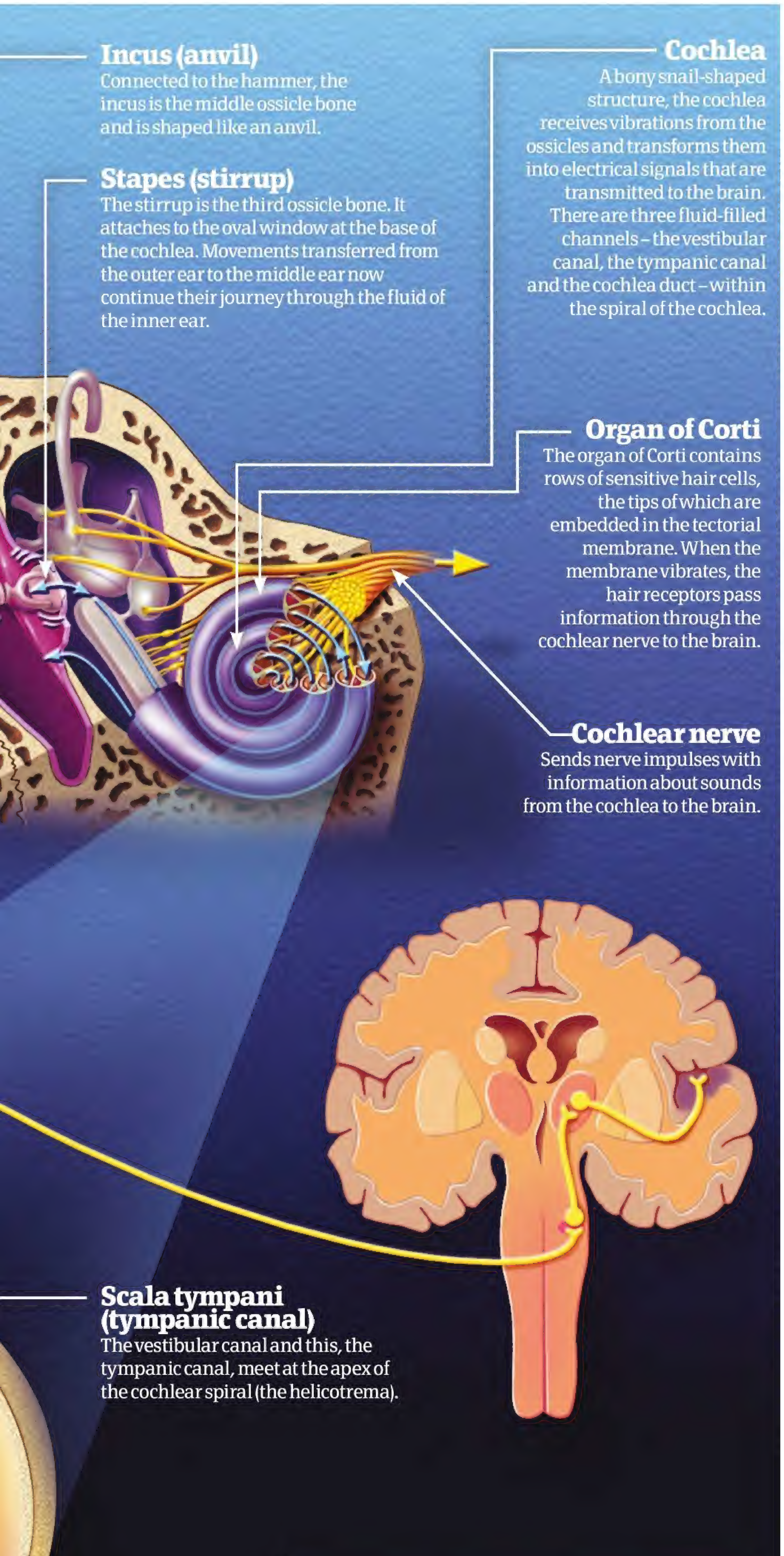
Consisting of air-filled cavities, labyrinthine fluid-filled channels and highly sensitive cells, the ear has external, middle and internal parts. The outer ear consists of a skin-covered flexible cartilage flap called the 'auricle', or 'pinna'. This feature is shaped to gather sound waves and amplify them before they enter the ear for processing and transmission to the brain. The first thing a sound wave entering the ear encounters is the sheet of tightly pulled tissue separating the outer and middle ear. This tissue is the eardrum, or tympanic membrane, and it vibrates as sound waves hit it.

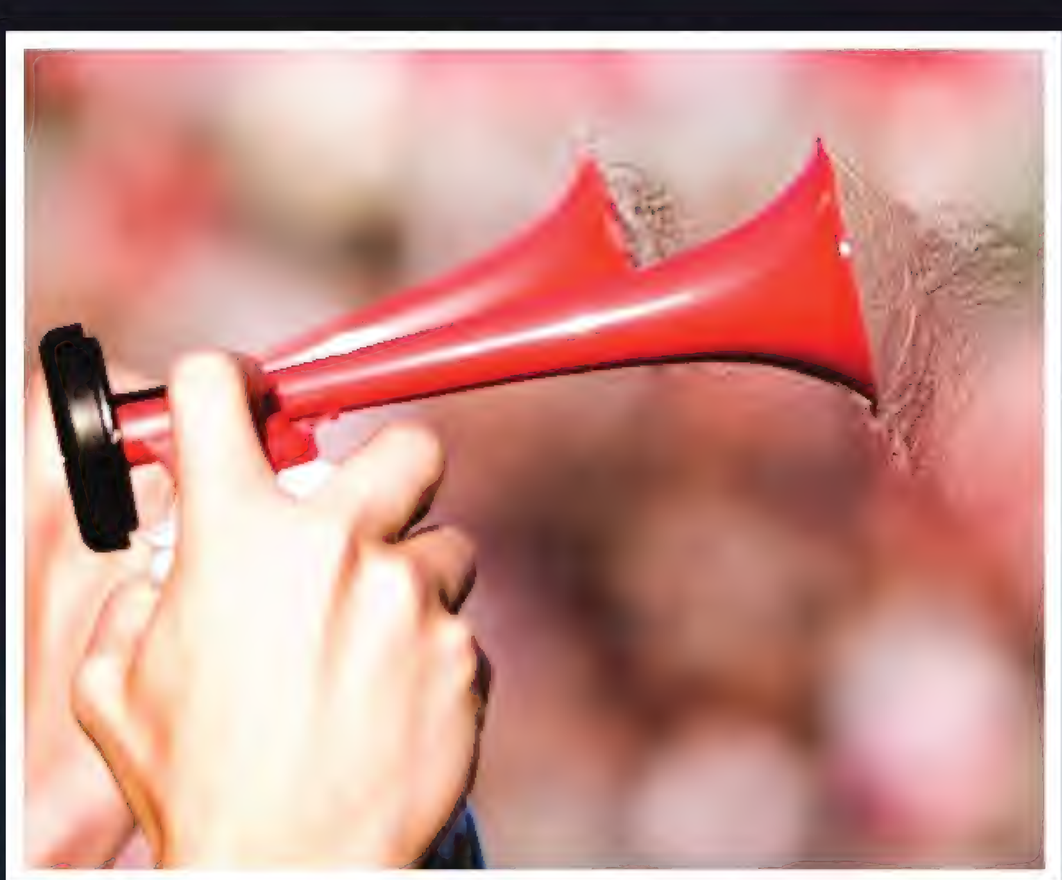
Beyond the eardrum, in the air-filled cavity of the middle ear, are three tiny bones called the 'ossicles'. These are the smallest bones in your entire body. Sound vibrations hitting the eardrum pass to the first ossicle, the malleus (hammer). Next the waves proceed along the incus (anvil) and then on to the (stapes) stirrup. The stirrup presses against a thin layer of tissue called the 'oval window', and this membrane enables sound waves to enter the fluid-filled inner ear.

The inner ear is home to the cochlea, which consists of watery ducts that channel the vibrations, as ripples, along the cochlea's spiraling tubes. Running through the middle of the cochlea is the organ of Corti, which is lined with minute sensory hair cells that pick up on the vibrations and generate nerve impulses that are sent to the brain as electrical signals. The brain can interpret these signals as sounds.





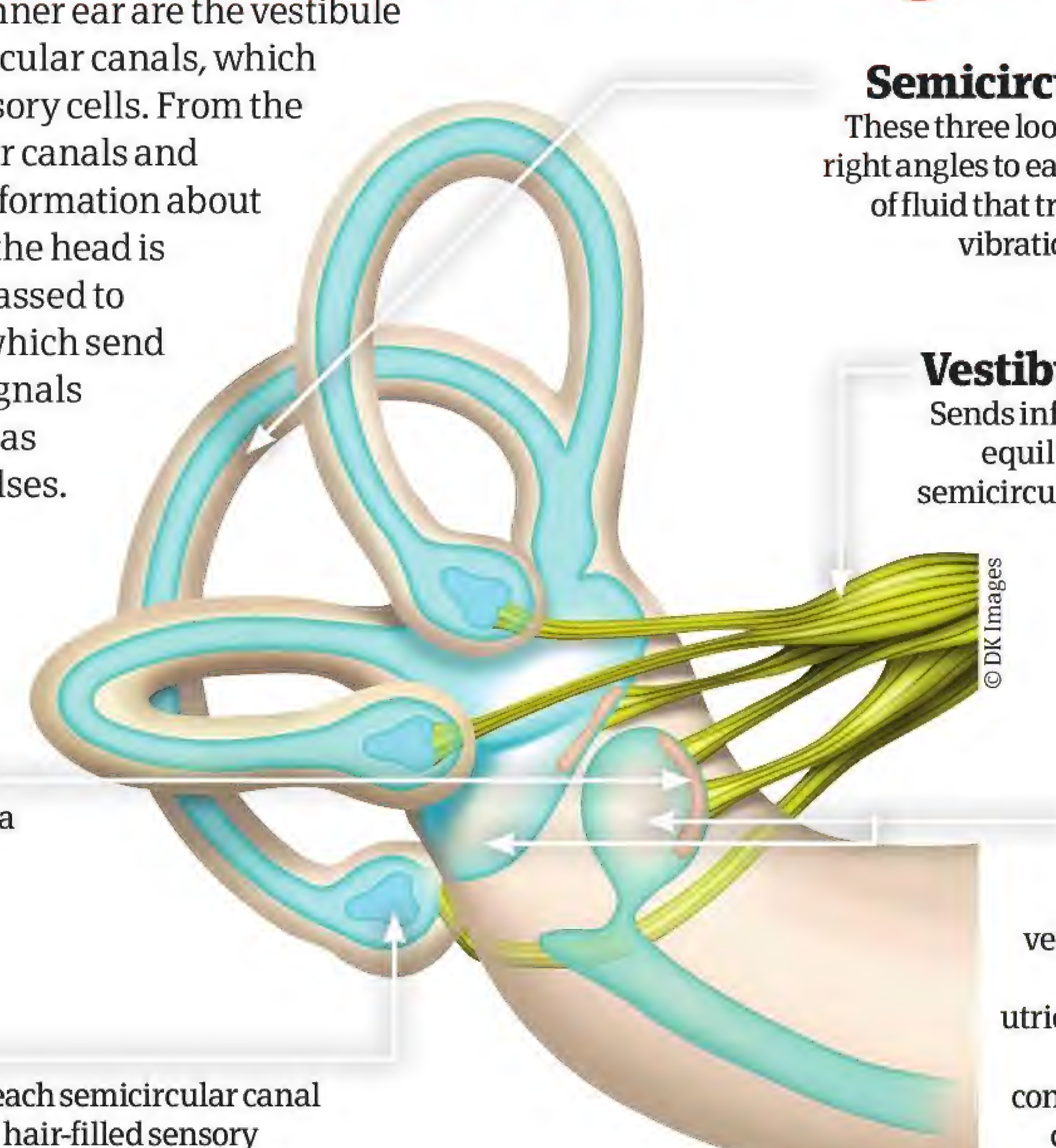




Think of sounds as movements, or disturbances of air, that create waves

The vestibular system

Inside the inner ear are the vestibule and semicircular canals, which feature sensory cells. From the semicircular canals and maculae, information about which way the head is moving is passed to receptors, which send electrical signals to the brain as nerve impulses.



A sense of balance

The vestibular system functions to give you a sense of which way your head is pointing in relation to gravity. It enables you to discern whether your head is upright or not, as well as helping you to maintain eye contact with stationary objects while your head is turning.

Also located within the inner ear, but less to do with sound and more concerned with the movement of your head, are the semicircular canals. Again filled with fluid, these looping ducts act like internal accelerometers that can detect acceleration (ie, movement of your head) in three different directions due to the positioning of the loops along different planes. Like the organ of Corti, the semicircular canals employ tiny hair cells to sense movement. The canals are connected to the auditory nerve at the back of the brain.

Your sense of balance is so complex that the area of your brain that's dedicated to this one role involves the same number of cells as the rest of your brain cells put together.

The surfer's semicircular canals are as crucial as his feet when it comes to staying on his board

Exploring the sensory system

The complex senses of the human body and how they interact is vital to the way we live day to day

The sensory system is what enables us to experience the world. It can also warn us of danger, trigger memories and protect us from damaging stimuli, such as scorching hot surfaces. The human sensory system is highly developed, with its many components detecting both physical and emotional properties of the environment. For example, it can interpret chemical molecules in the air into smells, moving molecules of sound into noises and pressure placed on the skin into touch. Indeed, some of our senses are so finely tuned they allow reactions within milliseconds of detecting a new sensation.

The five classic senses are sight, hearing, smell, taste and touch. We need senses not only to interpret the world around us, but also to function within it. Our senses enable us to modify our movements and thoughts, and sometimes they directly feed signals into muscles. The sensory nervous system that lies behind this is made up of receptors, nerves and dedicated parts of the brain.

There are thousands of different stimuli that can trigger our senses, including light, heat, chemicals in food and pressure. These 'stimulus modalities' are then detected by specialised receptors, which convert them into sensations such as hot and cold, tastes, images and touch. The incredible receptors – like the eyes, ears, nose, tongue and skin – have adapted over time to work seamlessly together and without having to be actively 'switched on'.

However, sometimes the sensory system can go wrong. There are hundreds of diseases of the senses, which can have both minor effects, or a life-changing impact. For example, a blocked ear can affect your balance, or a cold your ability to smell – but these things don't last for long.

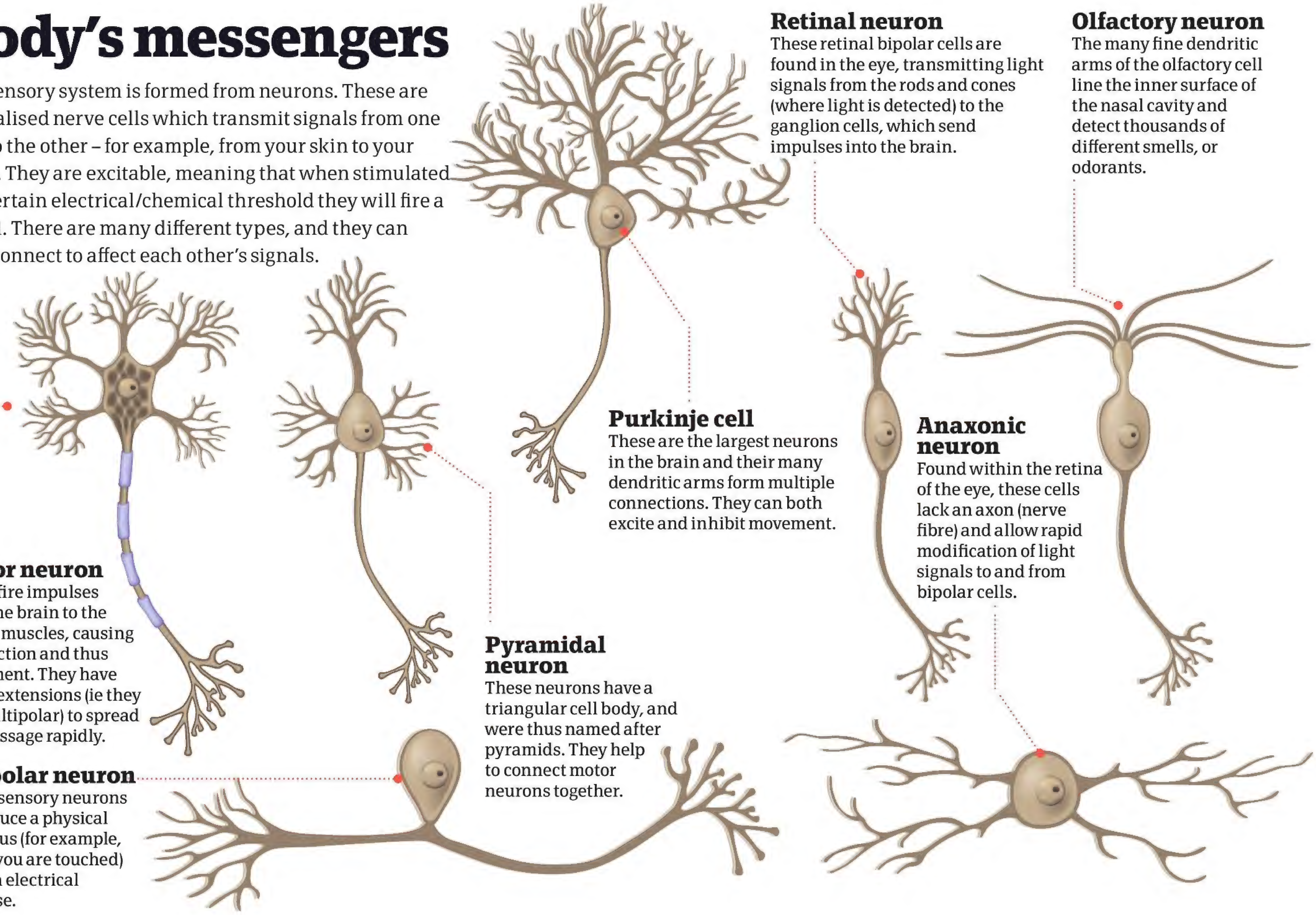
In contrast, say, after a car accident severing the spinal cord, the damage can be permanent. There are some very specific problems that the sensory system can bring as well. After an amputation, the brain can still detect signals from the nerves that used to connect to the lost limb. These sensations can cause excruciating pain; this particular condition is known as phantom limb syndrome.

However the sensory system is able to adapt to change, with the loss of one often leading to others being heightened. Our senses normally function to gently inhibit each other in order to moderate individual sensations. The loss of sight from blindness is thought to lead to strengthening of signals from the ears, nose and tongue. Having said this, it's certainly not universal among the blind, being more common in people who have been blind since a young age or from birth. Similarly, some people who listen to music like to close their eyes, as they claim the loss of visual input can enhance the audio experience.

Although the human sensory system is well developed, many animals out-perform us. For example, dogs can hear much higher-pitched sounds, while sharks have a far better sense of smell – in fact, they can sniff out a single drop of blood in a million drops of water!

Body's messengers

The sensory system is formed from neurons. These are specialised nerve cells which transmit signals from one end to the other – for example, from your skin to your brain. They are excitable, meaning that when stimulated to a certain electrical/chemical threshold they will fire a signal. There are many different types, and they can interconnect to affect each other's signals.



Retinal neuron
These retinal bipolar cells are found in the eye, transmitting light signals from the rods and cones (where light is detected) to the ganglion cells, which send impulses into the brain.

Olfactory neuron
The many fine dendritic arms of the olfactory cell line the inner surface of the nasal cavity and detect thousands of different smells, or odorants.

Purkinje cell
These are the largest neurons in the brain and their many dendritic arms form multiple connections. They can both excite and inhibit movement.

Anaxonic neuron
Found within the retina of the eye, these cells lack an axon (nerve fibre) and allow rapid modification of light signals to and from bipolar cells.

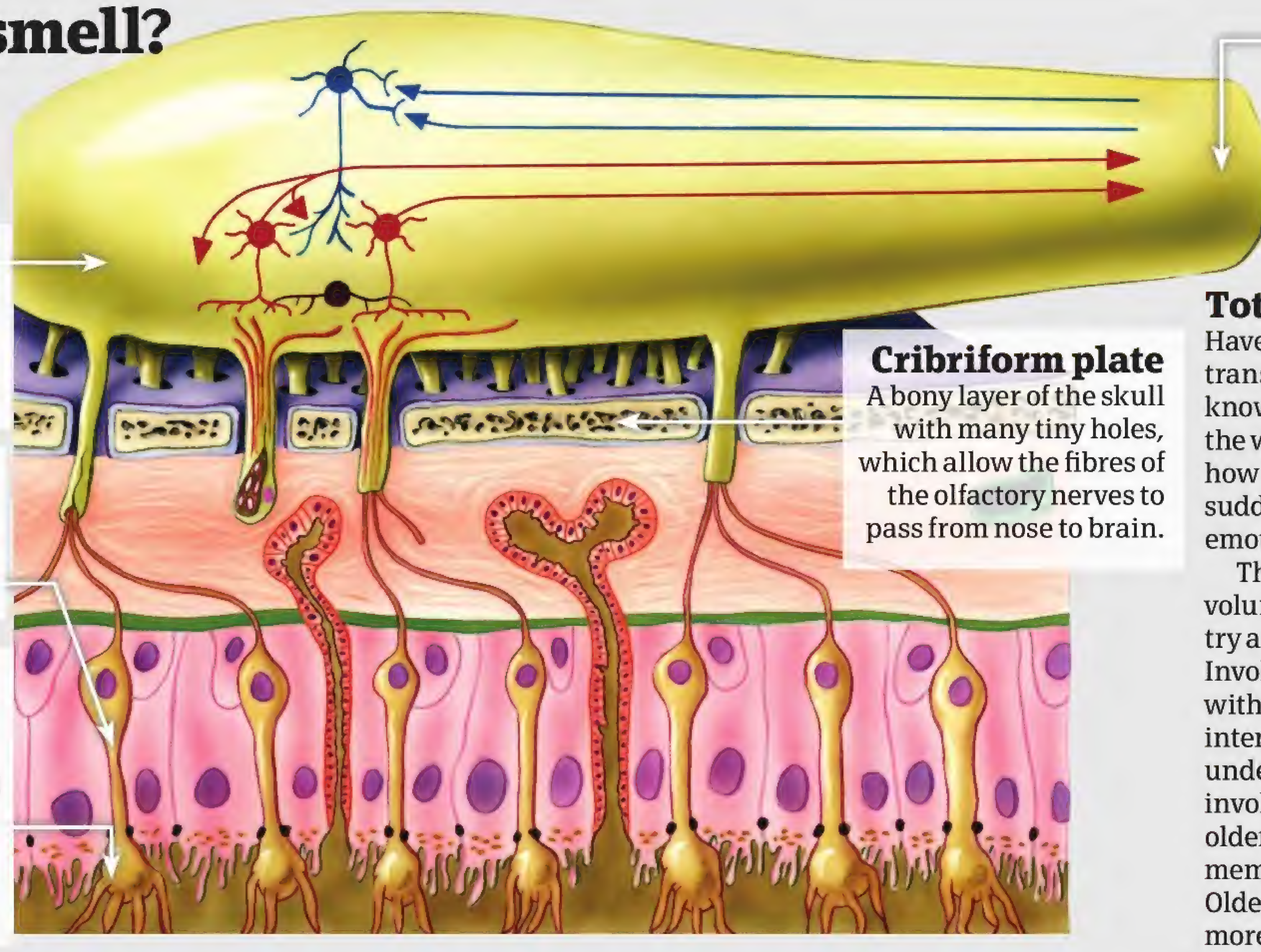
Motor neuron
These fire impulses from the brain to the body's muscles, causing contraction and thus movement. They have lots of extensions (ie they are multipolar) to spread the message rapidly.

Pyramidal neuron
These neurons have a triangular cell body, and were thus named after pyramids. They help to connect motor neurons together.

Unipolar neuron
These sensory neurons transduce a physical stimulus (for example, when you are touched) into an electrical impulse.

How do we smell?

Find out how our nose and brain work together to distinguish scents



Olfactory bulb
Containing many types of cell, olfactory neurons branch out of here through the cribriform plate below.

Olfactory neuron
These neurons are highly adapted to detect a wide range of different odours.

Olfactory epithelium
Lining the nasal cavity, this layer contains the long extensions of the olfactory neurons and is where chemical molecules in air trigger an electric impulse.

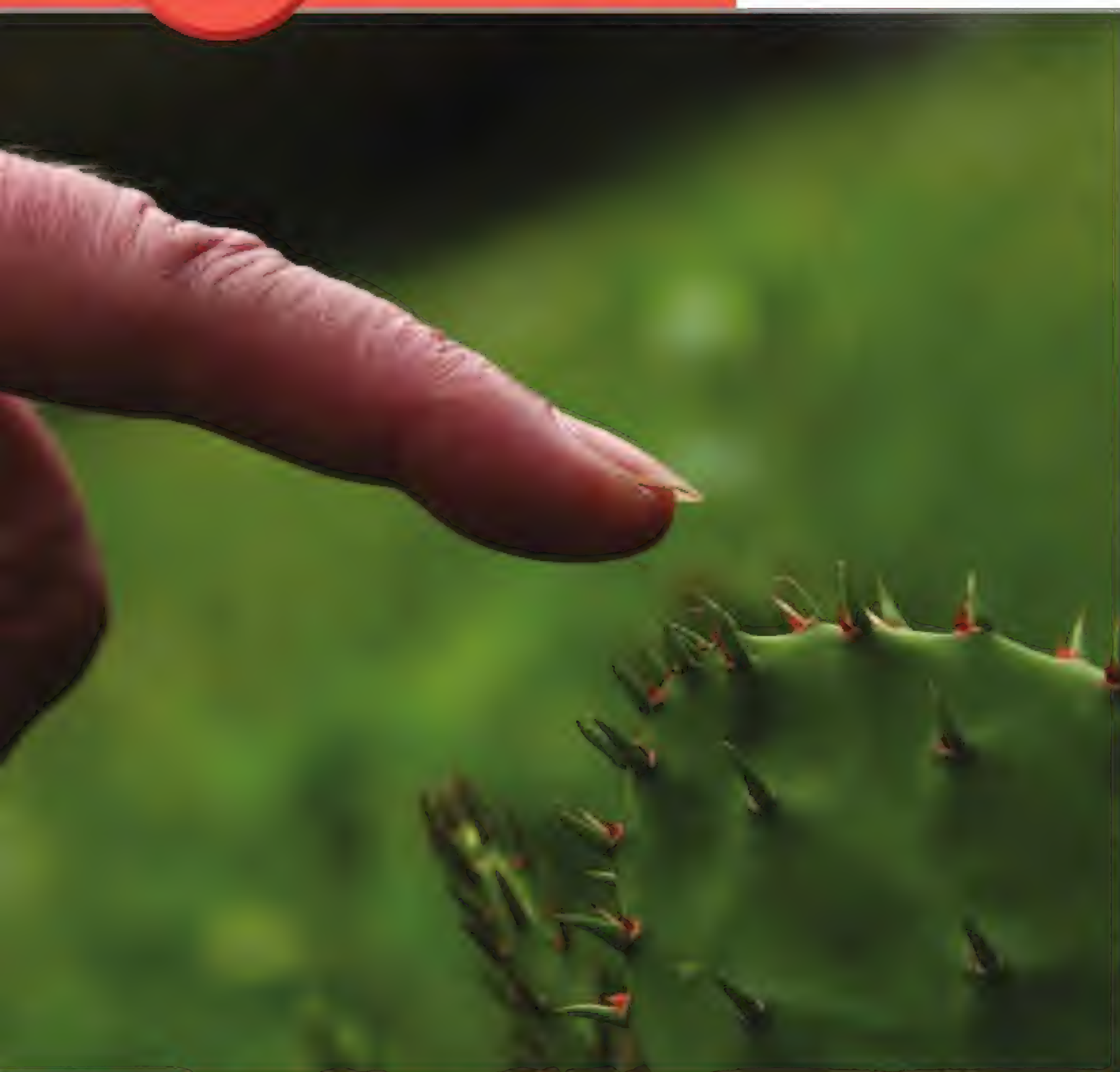
Cribriform plate
A bony layer of the skull with many tiny holes, which allow the fibres of the olfactory nerves to pass from nose to brain.

Olfactory nerve
New signals are rapidly transmitted via the olfactory nerve to the brain, which collates the data with sight and taste.

Total recall

Have you ever smelt something that transported you back in time? This is known as the Madeleine effect because the writer Marcel Proust once described how the scent of a madeleine cake suddenly evoked strong memories and emotions from his childhood.

The opposite type of recall is voluntary memory, where you actively try and remember a certain event. Involuntary memories are intertwined with emotion and so are often the more intense of the two. Younger children under the age of ten have stronger involuntary memory capabilities than older people, which is why these memories thrust you back to childhood. Older children use voluntary memory more often, eg when revising for exams.

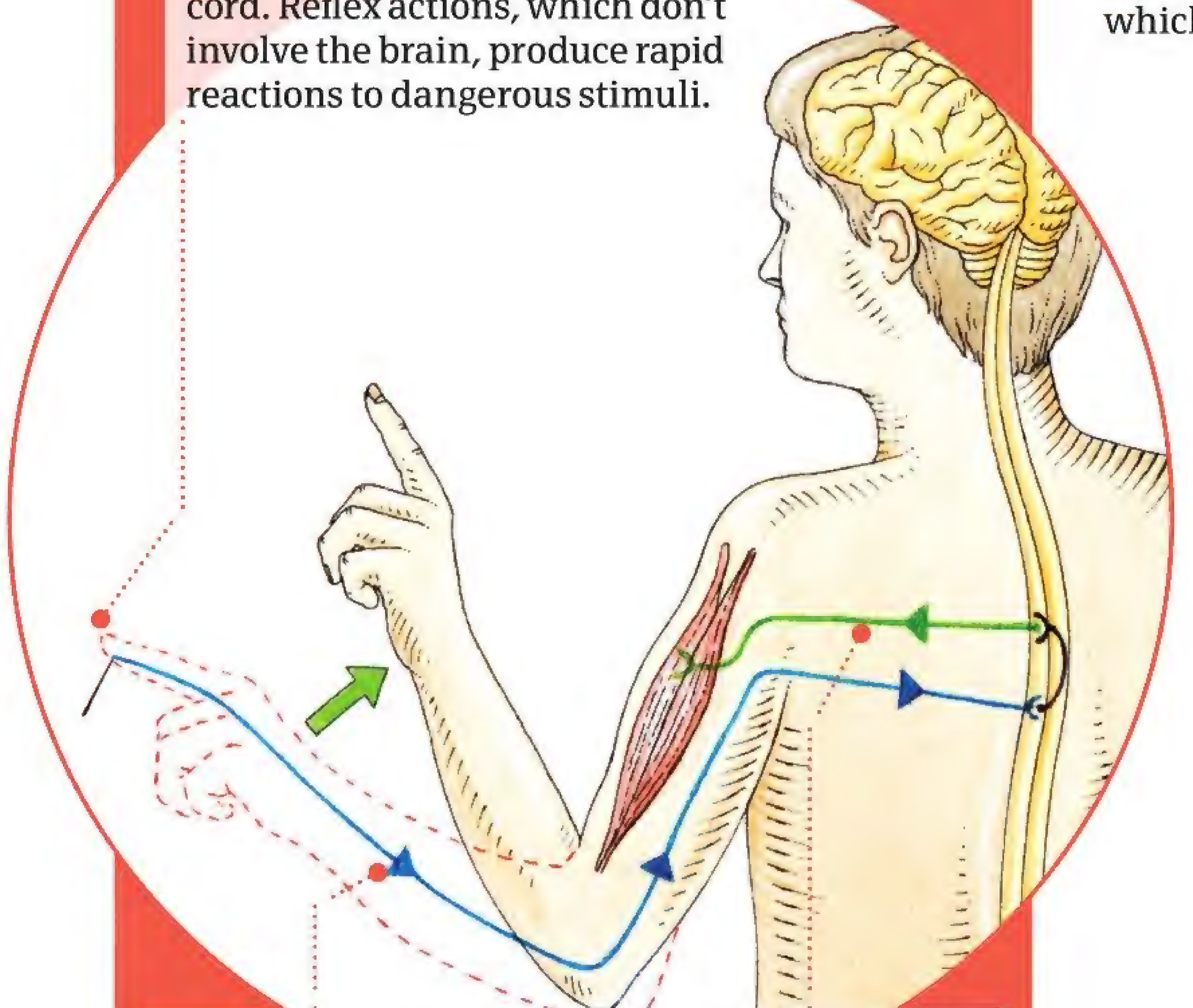


Understanding lightning reflexes

Have you ever felt something scorching hot or freezing cold, and pulled your hand away without even thinking about it? This reaction is a reflex. Your reflexes are the most vital and fastest of all your senses. They are carried out by the many 'reflex arcs' located throughout the body.

For example, a temperature-detecting nerve in your finger connects to a motor nerve in your spine, which travels straight to your biceps, creating a circular arc of nerves. By only having two nerves in the circuit, the speed of the reflex is as fast as possible. A third nerve transmits the sensation to the brain, so you know what's happened, but this nerve doesn't interfere with the arc; it's for your information only. There are other reflex arcs located within your joints, so that, say, if your knee gives way or you suddenly lose balance, you can compensate quickly.

1. Touch receptor
When a touch receptor is activated, information about the stimulus is sent to the spinal cord. Reflex actions, which don't involve the brain, produce rapid reactions to dangerous stimuli.

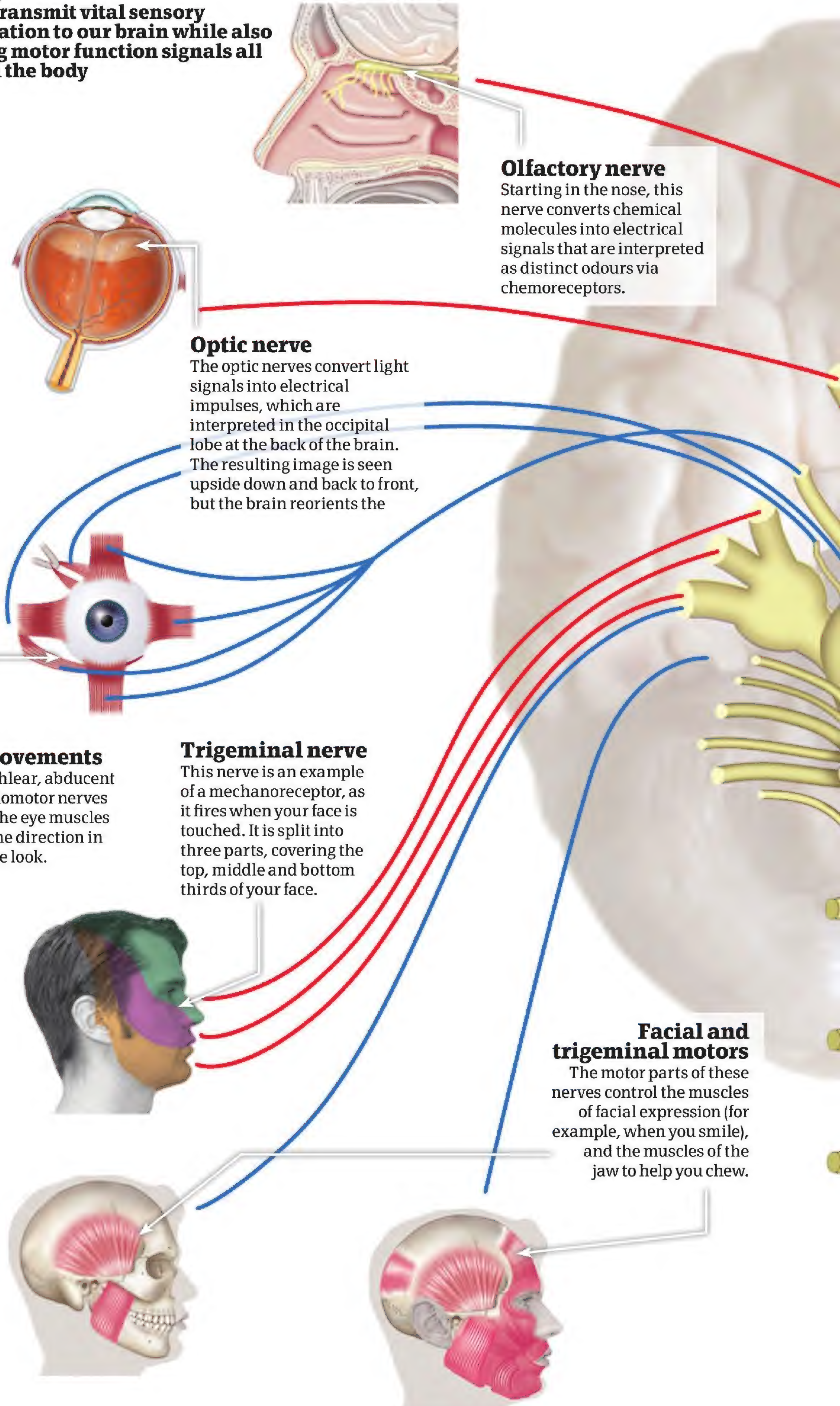


2. Signal sent to spine
When sensory nerve endings fire, information passes through nerve fibres to the spinal cord.

3. Motor neurons feed back
The signals trigger motor neurons that initiate their own impulses that feed back to the muscle, telling it to move the body part.

Key nerves

These transmit vital sensory information to our brain while also sending motor function signals all around the body



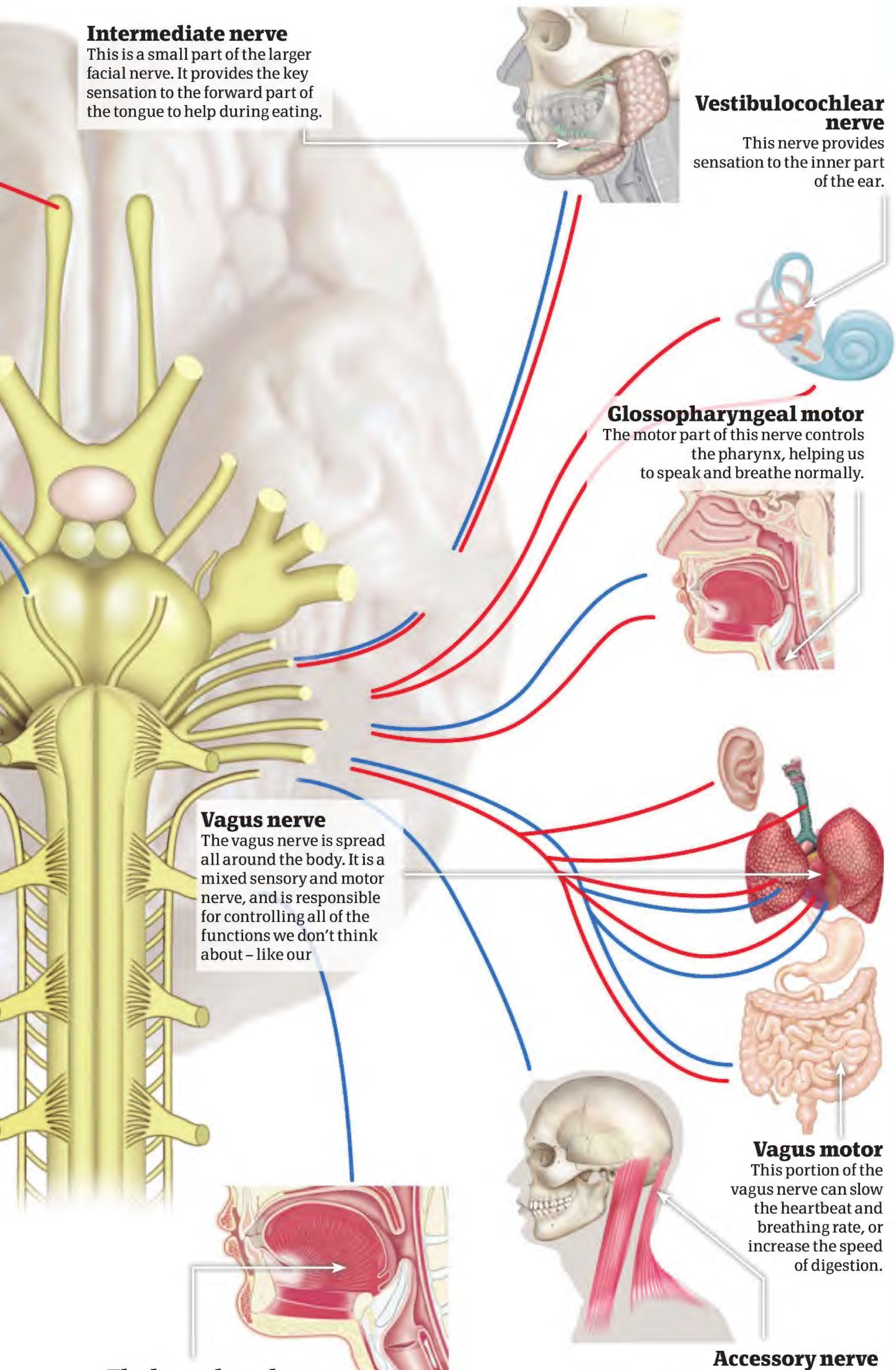
Olfactory nerve
Starting in the nose, this nerve converts chemical molecules into electrical signals that are interpreted as distinct odours via chemoreceptors.

Optic nerve
The optic nerves convert light signals into electrical impulses, which are interpreted in the occipital lobe at the back of the brain. The resulting image is seen upside down and back to front, but the brain reorients the

Eye movements
The trochlear, abducent and oculomotor nerves control the eye muscles and so the direction in which we look.

Trigeminal nerve
This nerve is an example of a mechanoreceptor, as it fires when your face is touched. It is split into three parts, covering the top, middle and bottom thirds of your face.

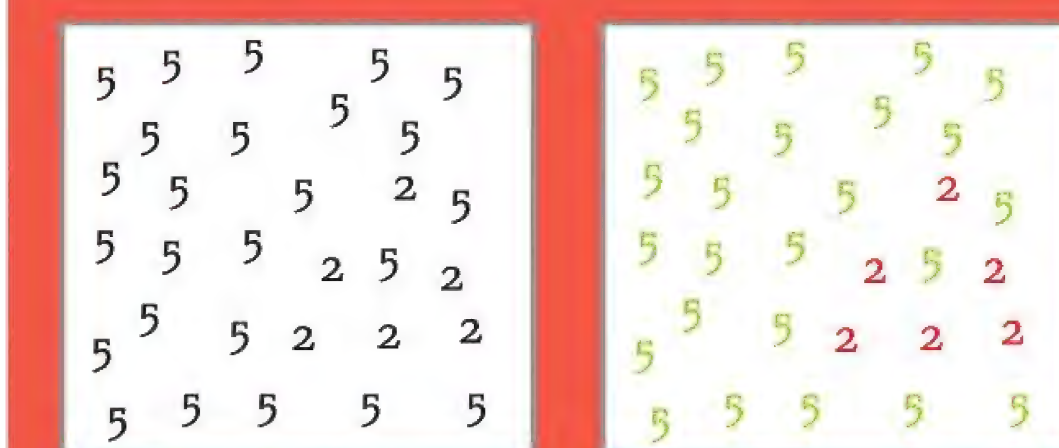
Facial and trigeminal motors
The motor parts of these nerves control the muscles of facial expression (for example, when you smile), and the muscles of the jaw to help you chew.



Crossed senses

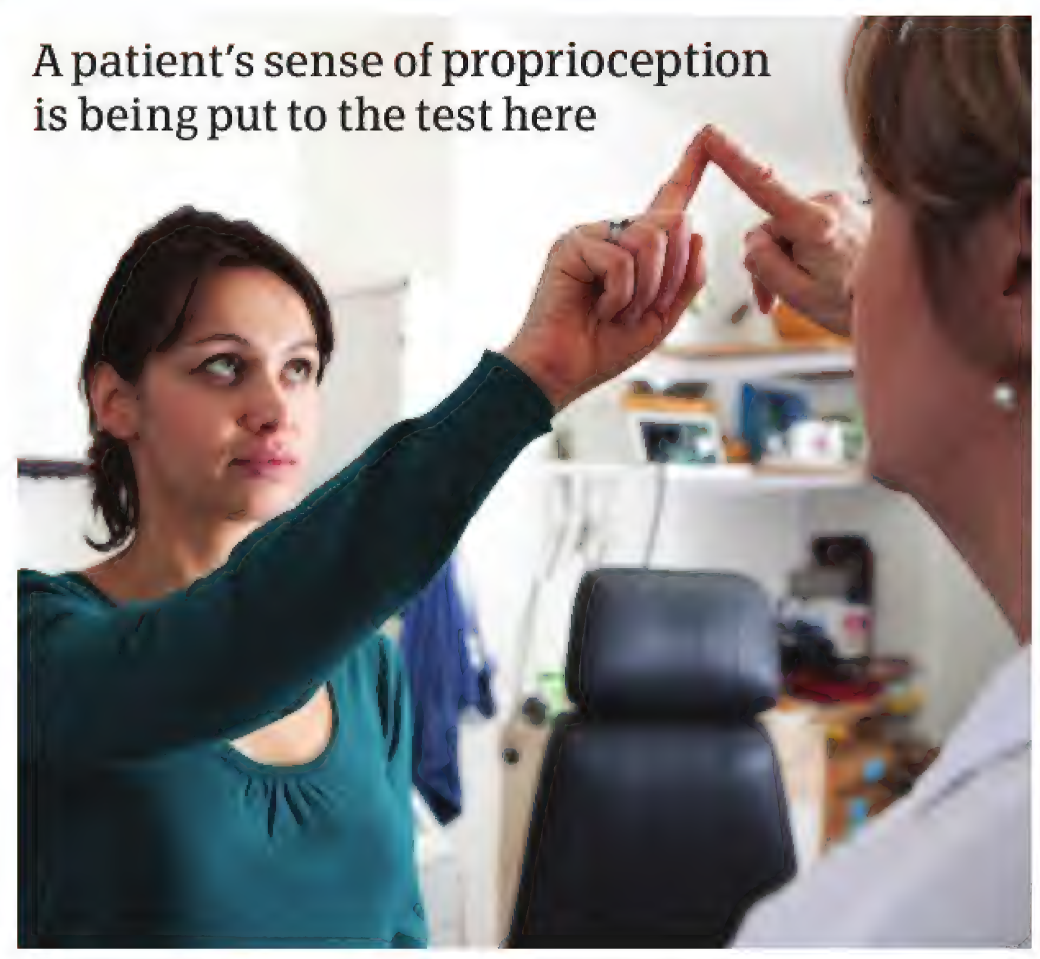
Synaesthesia is a fascinating, if yet completely understood, condition. In some people, two or more of the five senses become completely linked so when a single sensation is triggered, all the linked sensations are activated too. For example, the letter 'A' might always appear red, or seeing the number '1' might trigger the taste of apples. Sights take on smells, a conversation can take on tastes and music can feel textured.

People with synaesthesia certainly don't consider it to be a disorder or a disease. In fact, many do not think what they sense is unusual, and they couldn't imagine living without it. It often runs in families and may be more common than we think. More information about the condition is available from the UK Synaesthesia Association (**www.uksynaesthesia.com**).



Non-synaesthetes struggle to identify a triangle of 2s among a field of number 5s.

But a synaesthete who sees 2s as red and 5s as green can quickly pick out the triangle.



A patient's sense of proprioception is being put to the test here

Is there really a 'sixth sense'?

Our sense of balance and the position of our bodies in space are sensations we rarely think about and so are sometimes thought of as a 'sixth sense'. There is a whole science behind them though, and they are collectively called proprioception. There are nerves located throughout the musculoskeletal system (for example, within your muscles, tendons, ligaments and joints) whose job it is to send information on balance and posture back to the brain. The brain then interprets this information rapidly and sends instructions back to the muscles to allow for fine adjustments in balance. Since you don't have to think about it and you can't switch it off, you don't know how vital these systems are until they're damaged. Sadly some medical conditions, including strokes, can affect our sense of proprioception, making it difficult to stand, walk, talk and move our limbs.

THE OTHER SENSES

Discover the ten senses you never knew you had




The five classic human senses get all of the attention, so it might surprise you to know that there are several more senses working quietly in the background. Take something as simple as sitting down to eat your dinner. All five senses are active, taking in the sight and smell of the food on your plate, the taste and feel as you put it into your mouth, and the sound as you chew, but without your other senses, the experience would not be the same.

The simple act of sitting at the table and getting the food from the plate to your mouth is a sensory feat. You can't keep an eye on your limbs all the time, so the positions of your joints and the tension on your muscles is constantly measured, enabling you to eat without having to closely watch what you are doing. In order to stay balanced as you reach across the table, sensory information is quietly gathered by specialist structures in the inner ear.

Once the food is inside your mouth, one set of sensors provide information about the temperature, and another set of specialist nerves called nociceptors quickly alert you if the mouthful is dangerously hot or cold. At the same time, your blood and the fluid surrounding your central nervous system are monitored to make sure that levels of carbon dioxide and oxygen remain within normal limits, and your breathing rate is subconsciously adjusted.

As your stomach starts to fill up, stretch sensors feed back to the brain, turning down the signals that are telling you to keep eating, and when the part-digested food starts to hit your small intestine, sensors trigger the production of a hormone that flicks the switch telling you that you have had enough. The build-up of waste products is also closely monitored, and long after your meal is completed, sensors will alert you when it is time to get rid of anything that is left over.

So while the traditional five senses are the ones that we rely on most in our conscious interactions with the world around us, there are several more that work quietly in the background as we go about our daily lives.

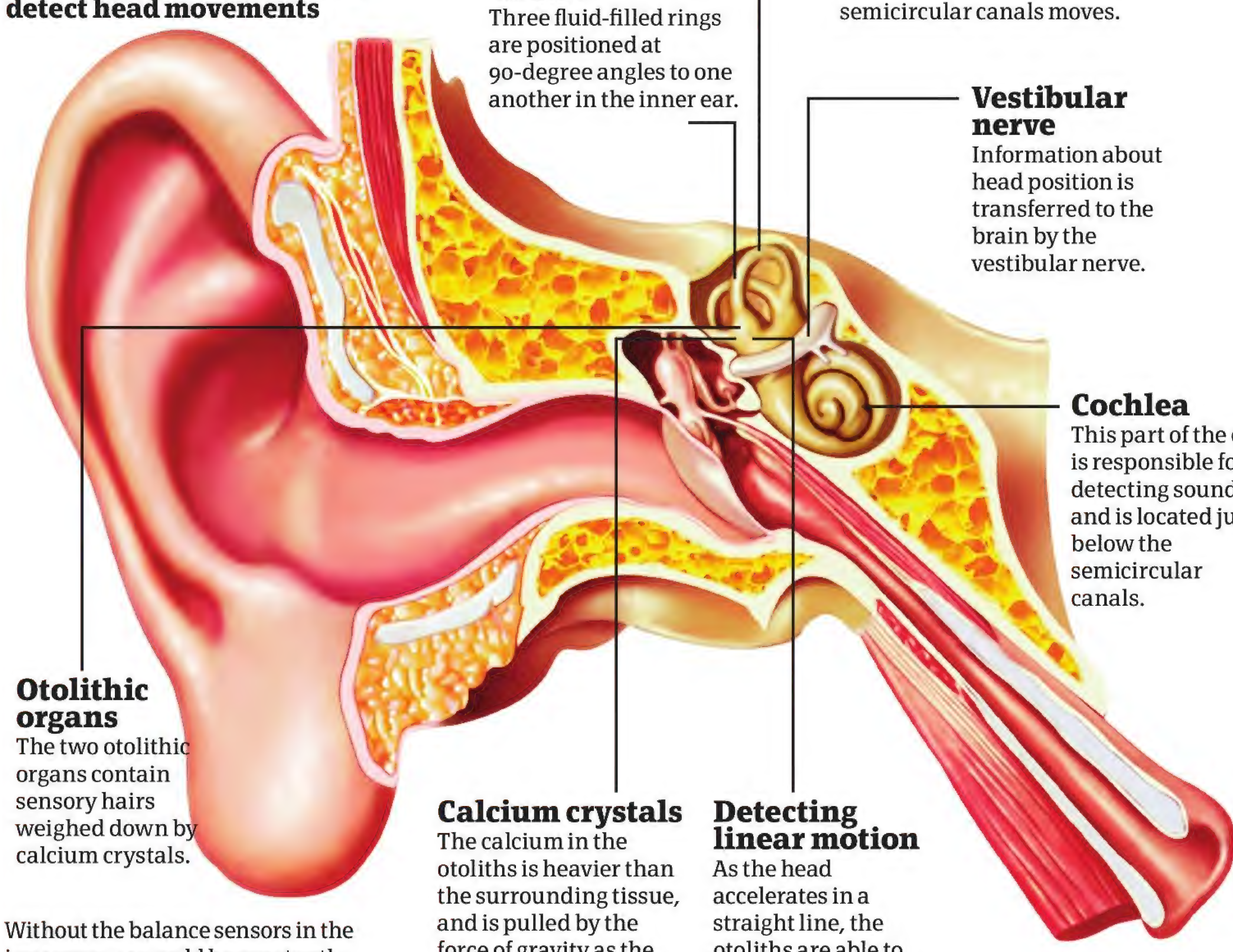
The brain uses a combination of signals from the eyes, ears, joints and muscles to maintain balance

Balance
(equilibrioception)

Our sense of balance is handled by the vestibular system in the inner ear, and provides vital feedback about head position and movement. Inside the ear there are three semicircular canals; each is filled with fluid. At one end of each canal is a bulge supporting a series of sensitive hairs. As you move your head, the fluid moves too, bending the tiny hairs and sending information about head rotation to the brain. There are also two organs called otoliths on each side of the head. These contain sensory hairs weighed down by calcium crystals that help to tell which way is up.

The sense of balance

The inner ear contains specialised structures that detect head movements



Semicircular canals
Three fluid-filled rings are positioned at 90-degree angles to one another in the inner ear.

Detecting head rotation
As the head rotates, the fluid in the semicircular canals moves.

Vestibular nerve
Information about head position is transferred to the brain by the vestibular nerve.

Cochlea
This part of the ear is responsible for detecting sound, and is located just below the semicircular canals.

Otolithic organs
The two otolithic organs contain sensory hairs weighed down by calcium crystals.

Calcium crystals
The calcium in the otoliths is heavier than the surrounding tissue, and is pulled by the force of gravity as the head moves.

Detecting linear motion
As the head accelerates in a straight line, the otoliths are able to detect the movement.

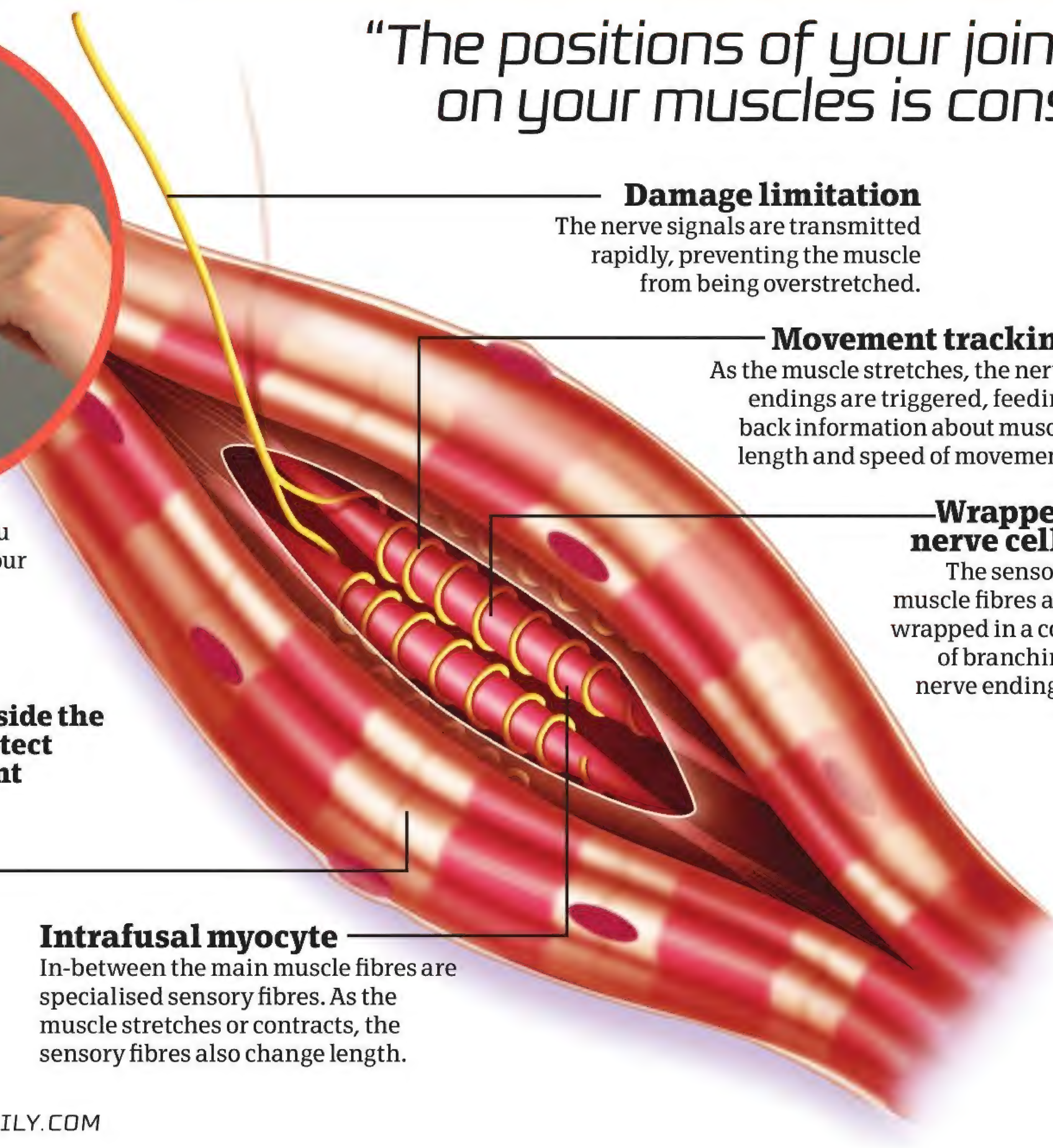
Without the balance sensors in the inner ear, we would be constantly dizzy and disorientated

"The positions of your joints and the tension on your muscles is constantly measured"

Without proprioception, you wouldn't be able to touch your nose with your eyes closed

Keeping

Specialised fibres inside the muscle are able to detect stretch and movement



Damage limitation
The nerve signals are transmitted rapidly, preventing the muscle from being overstretched.

Movement tracking
As the muscle stretches, the nerve endings are triggered, feeding back information about muscle length and speed of movement.

Wrapped nerve cells
The sensory muscle fibres are wrapped in a coil of branching nerve endings.

Extrafusal myocyte
The main muscle fibres are responsible for contraction, controlled by incoming nerve signals.

Intrafusal myocyte
In-between the main muscle fibres are specialised sensory fibres. As the muscle stretches or contracts, the sensory fibres also change length.

Movement
(proprioception)

Even the simplest movements would be a challenge without this sense; proprioception allows us to keep track of the position of our bodies in space without looking. This enables us to make the tiny adjustments that keep us from falling over when we are standing still, helps us to judge the distance each time we take a step, and allows us to coordinate complex movements like riding a bike or playing the piano. The receptors responsible are found in the joints, muscles and skin, and help to relay information about the angle and position of each joint, and the tension on our tendons and muscles, providing the brain with constant feedback.

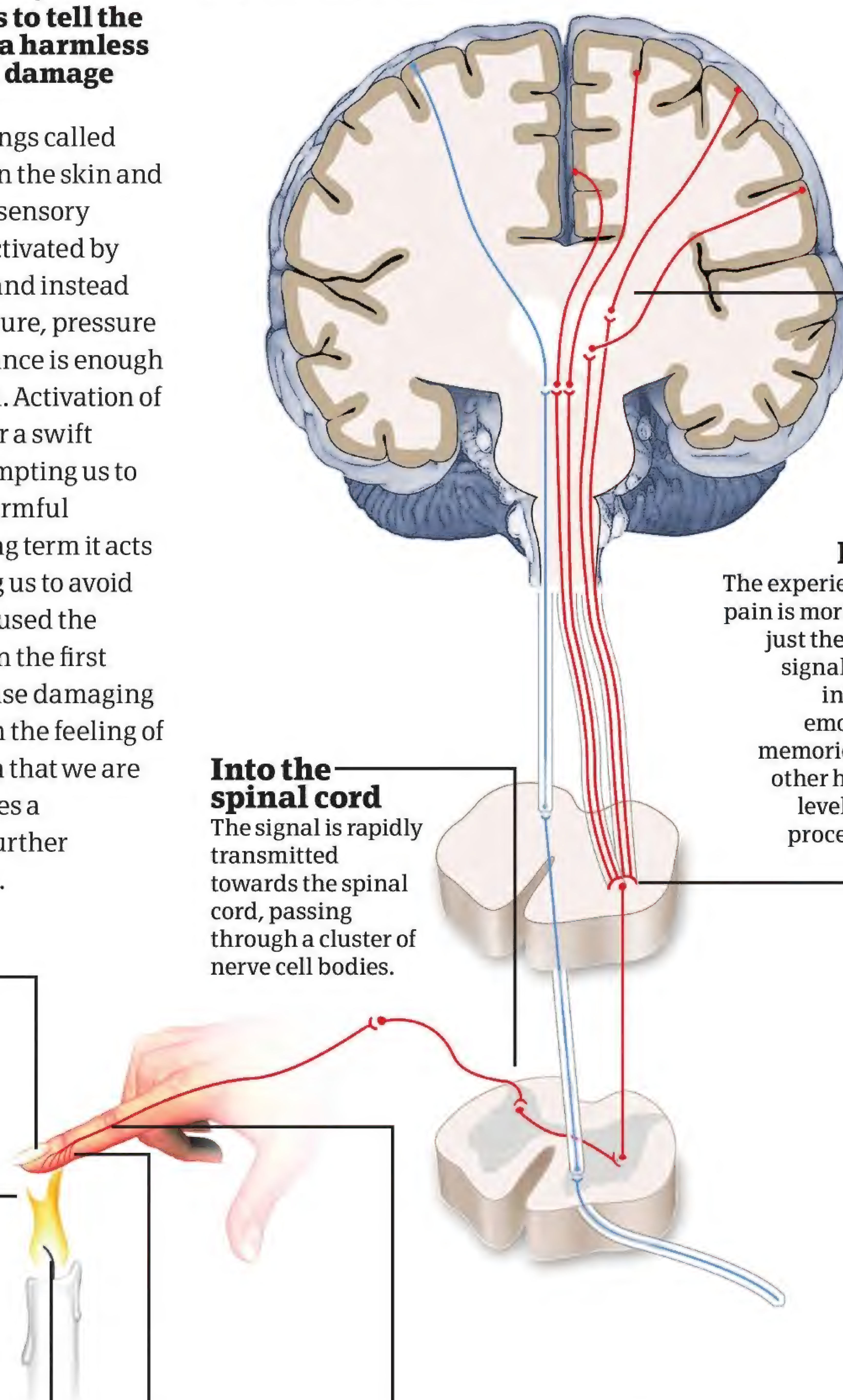
Pain (nociception)

This sense allows us to tell the difference between a harmless touch and potential damage

Specialised nerve endings called nociceptors are found in the skin and organs. Unlike normal sensory nerves, these are not activated by low-level stimulation, and instead wait until the temperature, pressure or level of a toxic substance is enough to cause the body harm. Activation of these nerves can trigger a swift withdrawal reflex, prompting us to move away from the harmful stimulus, and in the long term it acts as a deterrent, teaching us to avoid whatever it was that caused the unpleasant sensation in the first place. The ability to sense damaging stimuli is different from the feeling of pain, and the sensation that we are all familiar with involves a significant amount of further processing in the brain.

How we feel pain

Detecting damage helps to keep our bodies safe



Pain receptor
Nociceptors are only activated if tissue damage is imminent, alerting the body to potential danger.

Heat
Some nerves respond specifically to heat, becoming active at temperatures above 40-45 degrees Celsius (104-113 degrees Fahrenheit).

Cold
Other nerves respond to cold temperatures, and start to fire when temperatures drop below five degrees Celsius (41 degrees Fahrenheit).

Pressure
Some nociceptors respond to pressure, triggering when parts of the body are dangerously compressed.

Chemical
Some nociceptors respond to chemical signals of tissue damage, like the presence of acid, or the lack of oxygen.

Into the spinal cord
The signal is rapidly transmitted towards the spinal cord, passing through a cluster of nerve cell bodies.

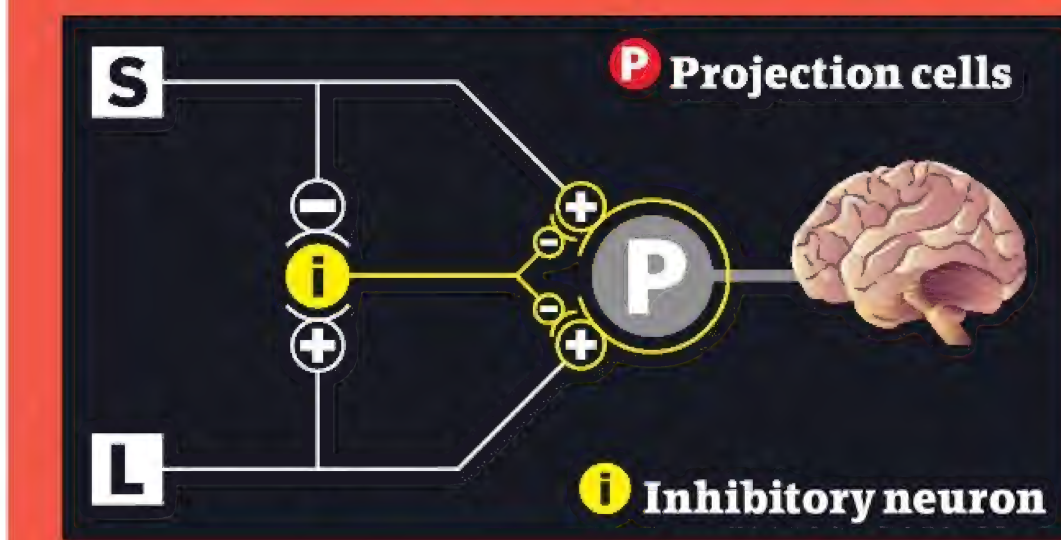
Pain
The experience of pain is more than just the nerve signals, and involves emotions, memories and other higher-level brain processing.

Towards the brain
The incoming signal can induce a rapid withdrawal reflex just by reaching the spinal cord, but the feeling of pain relies on signals travelling onwards to the brain.

"The ability to sense damaging stimuli is different from the feeling of pain"

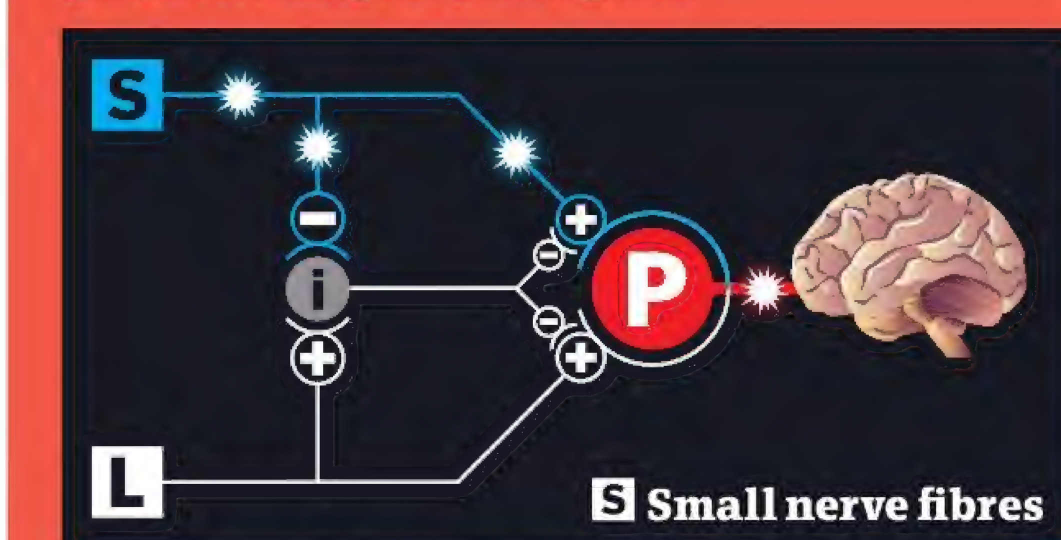
Numbing the pain

Have you ever put your finger in your mouth after shutting it in a door, or grabbed hold of your foot after stubbing your toe? Incoming signals from our other senses can switch off pain signals, preventing some of them from reaching the brain.



Pain gate
Nociceptive (pain-detecting) nerves send their signals towards the spinal cord before they go on to the brain, but in order to reach the brain they have to travel through a biological gate.

Inhibition of pain
Touch-sensitive nerves pass their messages through the same region as the pain signals. These nerve cells are larger and faster, and are able to close the gate, overriding the pain signals.

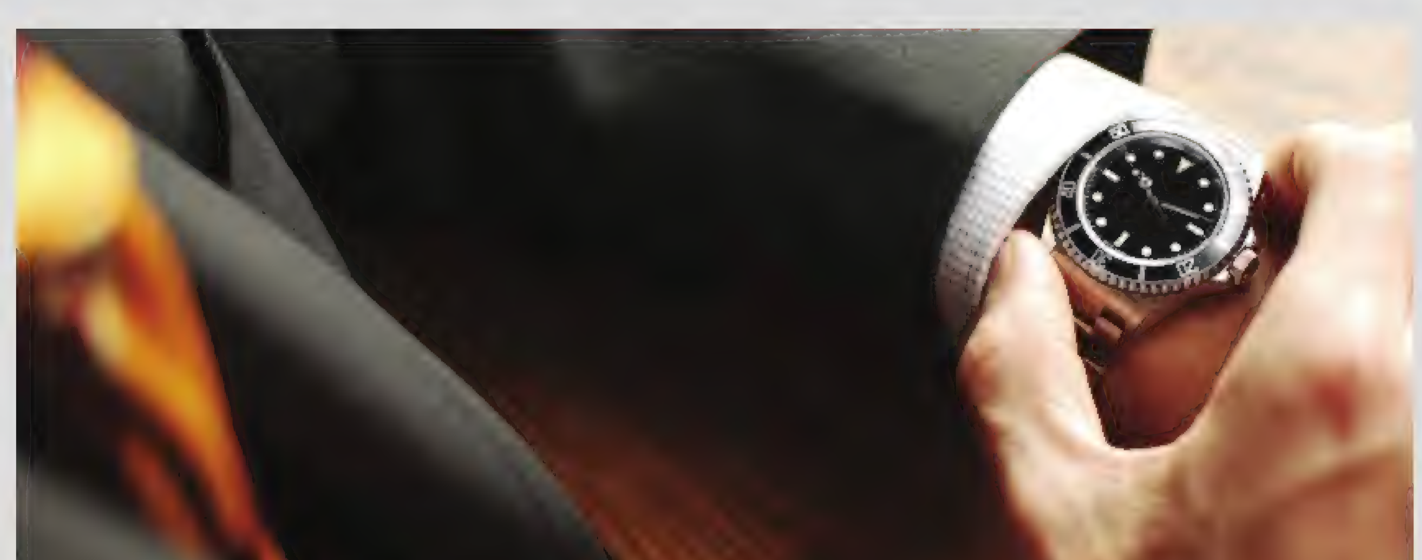


Pain signal
Without the input from the large nerve fibres, the gate is opened. This allows pain messages travelling along the smaller nerve fibres to pass through the spinal cord and onwards towards the brain.

Time (Chronoception)

Internal clocks help us to keep track of time

Even without a watch, we have a sense of the passage of time, but our body clock is not like any normal timepiece. The suprachiasmatic nucleus in the brain is the master clock, and it governs our daily cycle, or circadian rhythm. This 24-hour clock controls daily peaks and troughs in our hormone levels, influencing many behaviours, from eating to sleeping. For shorter tasks, scientists think that we might have several internal stopwatches keeping time inside our brains. As yet, the parts of the brain responsible for keeping these rhythms have not been discovered.



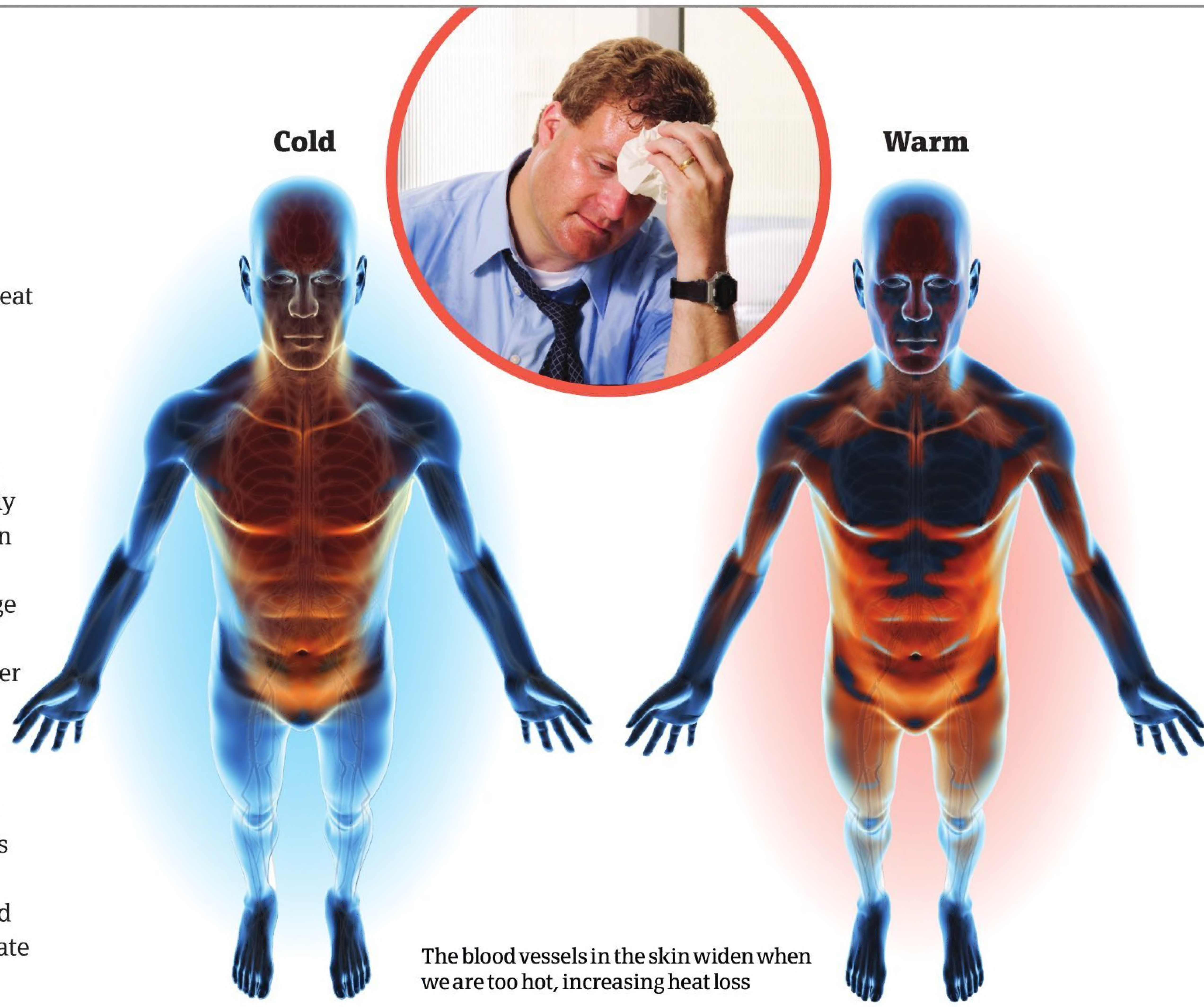
Our sense of time is not always reliable, and changes depending on our mood and environment

Temperature
(thermoception)

An internal thermostat keeps our body temperature at a constant 37°C (98.6°F)

It is crucial for our bodies to be able to detect heat and cold, firstly to ensure that our internal organs are kept at the right temperature to function properly, and secondly to prevent us being damaged by extremes. We are able to detect the temperature of our extremities by a series of nerves in the skin, while our core body temperature is monitored by a part of the brain known as the hypothalamus.

As warm-blooded animals, we generate huge amounts of heat as we burn sugars to release energy. This helps to keep us warm, but in order to maintain a constant temperature, adjustments need to be made continually to make up for changes in the environment or changes in our level of activity. For immediate changes in body temperature, the brain orders the body to shiver or sweat, and for more long-term regulation, the production of thyroid hormone is ramped up or down, altering the rate at which we burn sugars and generate heat.



The blood vessels in the skin widen when we are too hot, increasing heat loss

Itchiness

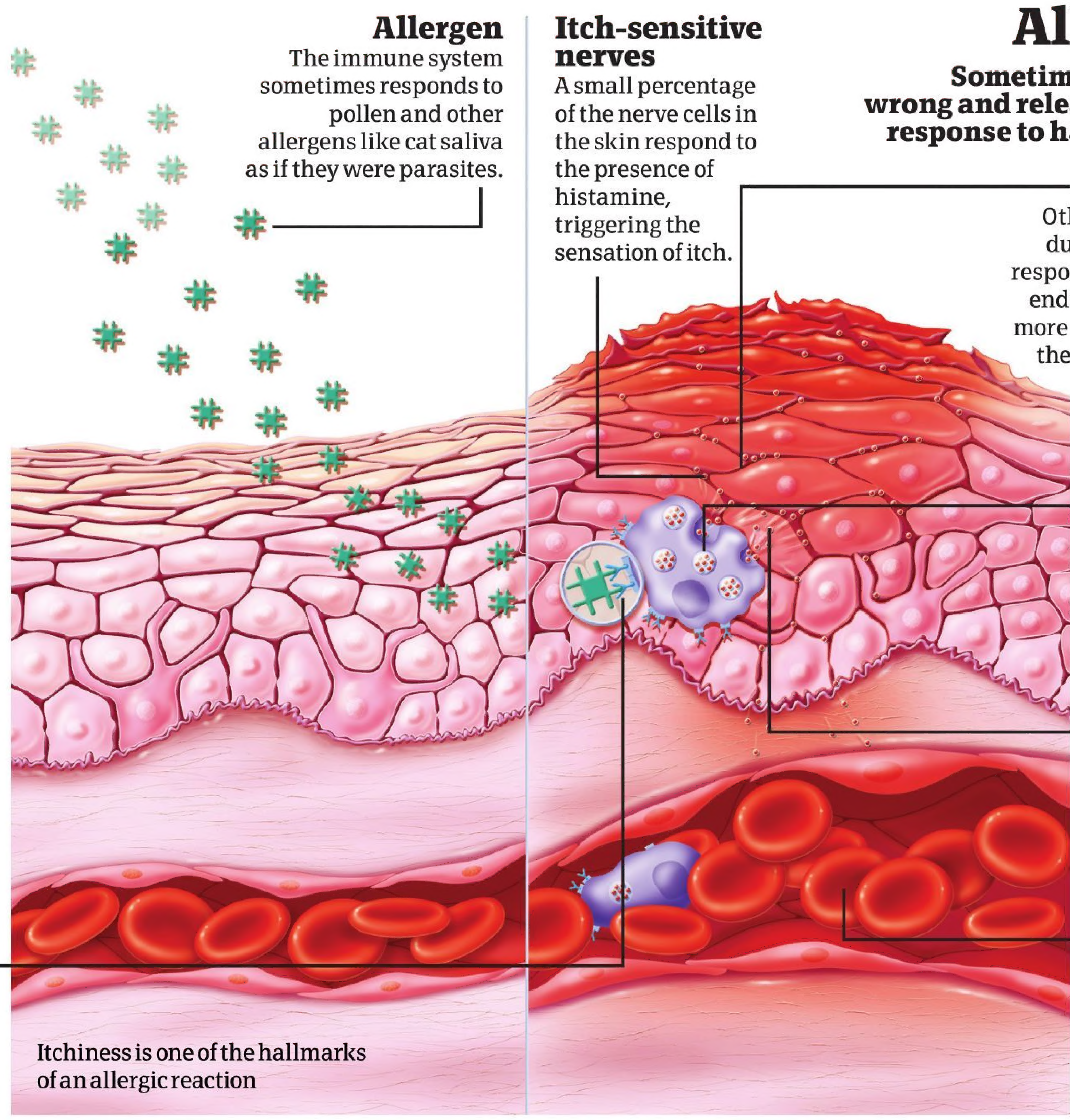
This unusual sensation is closely related to pain

Itchiness is the body's way of alerting us to parasites and irritants. It prompts a reflex scratch response, which scientists think is to draw our attention to that area of the body so any irritant can be eliminated. The exact science of itching is still unclear, but one of the most well studied culprits is a molecule known as histamine. Parasites like biting insects and worms often produce chemicals known as proteases, which help them to break through the barrier of the skin. These proteases trigger white blood cells to release histamine, which in turn activates our body's itch-sensitive nerve cells.

Allergen detection
The immune system sometimes mistakenly produces antibodies to attack harmless allergens. Mast cells then use these antibodies to detect when more allergens arrive.

Allergen
The immune system sometimes responds to pollen and other allergens like cat saliva as if they were parasites.

Itch-sensitive nerves
A small percentage of the nerve cells in the skin respond to the presence of histamine, triggering the sensation of itch.



Itchiness is one of the hallmarks of an allergic reaction

Allergic itch

Sometimes the body gets it wrong and releases histamine in response to harmless allergens

Extra sensitive
Other chemicals released during the inflammatory response sensitise the nerve endings, making them fire more easily and magnifying the sensation of itchiness.

Mast cell
These specialised immune cells behave like sentry towers in the skin. Their normal function is to respond rapidly to the presence of parasites.

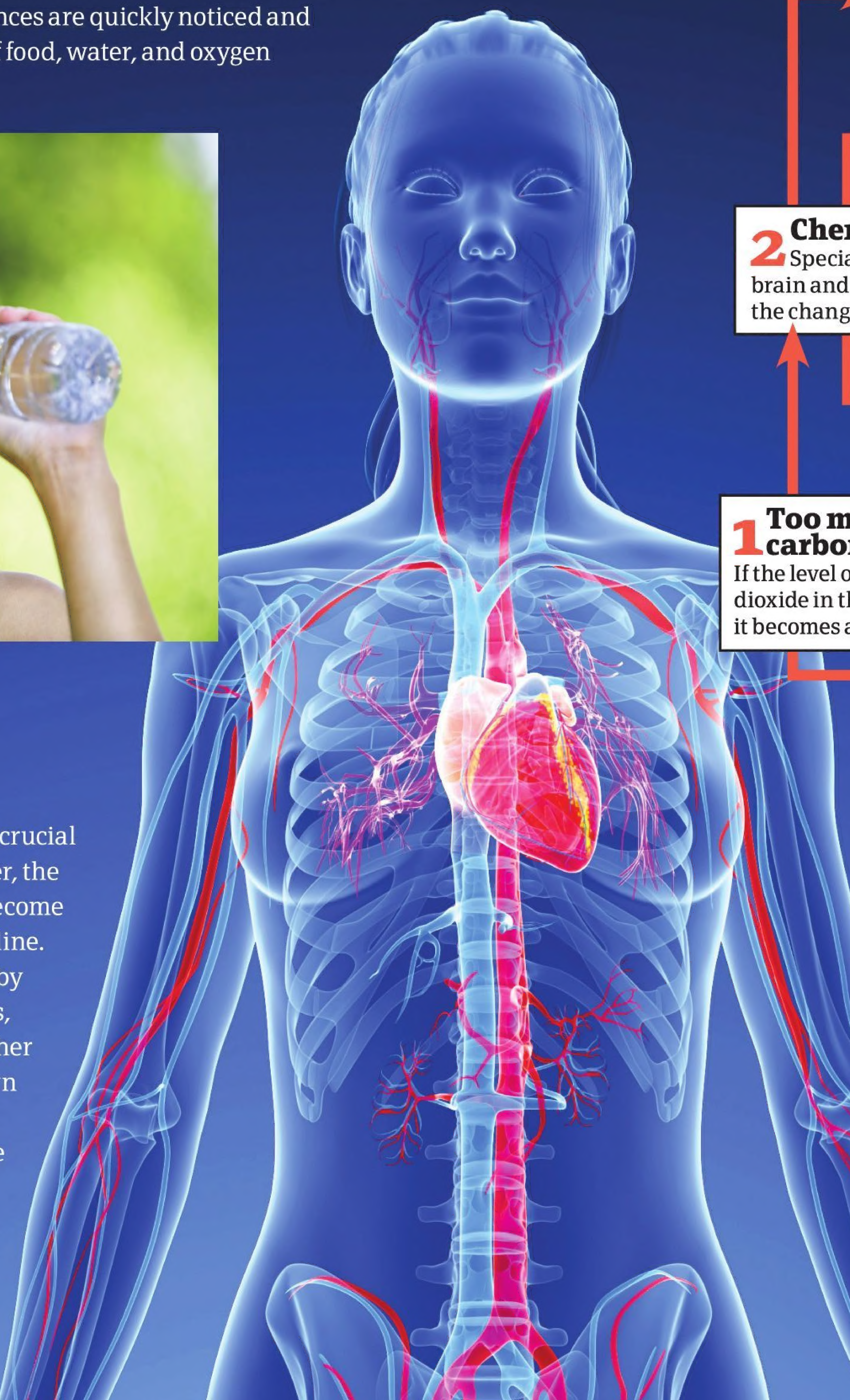
Histamine
This small molecule is responsible for the itchiness associated with allergic reactions.

Leaky vessels
Histamine also makes local blood vessels leaky, allowing more white blood cells to enter the area.

Internal sensors

Specialist sensory cells inside the body supply the brain with information about vital systems

We are all familiar with the senses that allow us to interact with our external environment, but behind the scenes, we need to constantly keep track of events happening on the inside. If we didn't, our tissues would quickly run out of fuel and oxygen, and waste products would start to build up. The state of the body is constantly monitored by specialised sensory cells in the brain and organ systems, ensuring that any imbalances are quickly noticed and corrected, helping to ensure that the supply of food, water, and oxygen always meets the demand.



Thirst

Sensing the water level in our bodies prevents dangerous dehydration

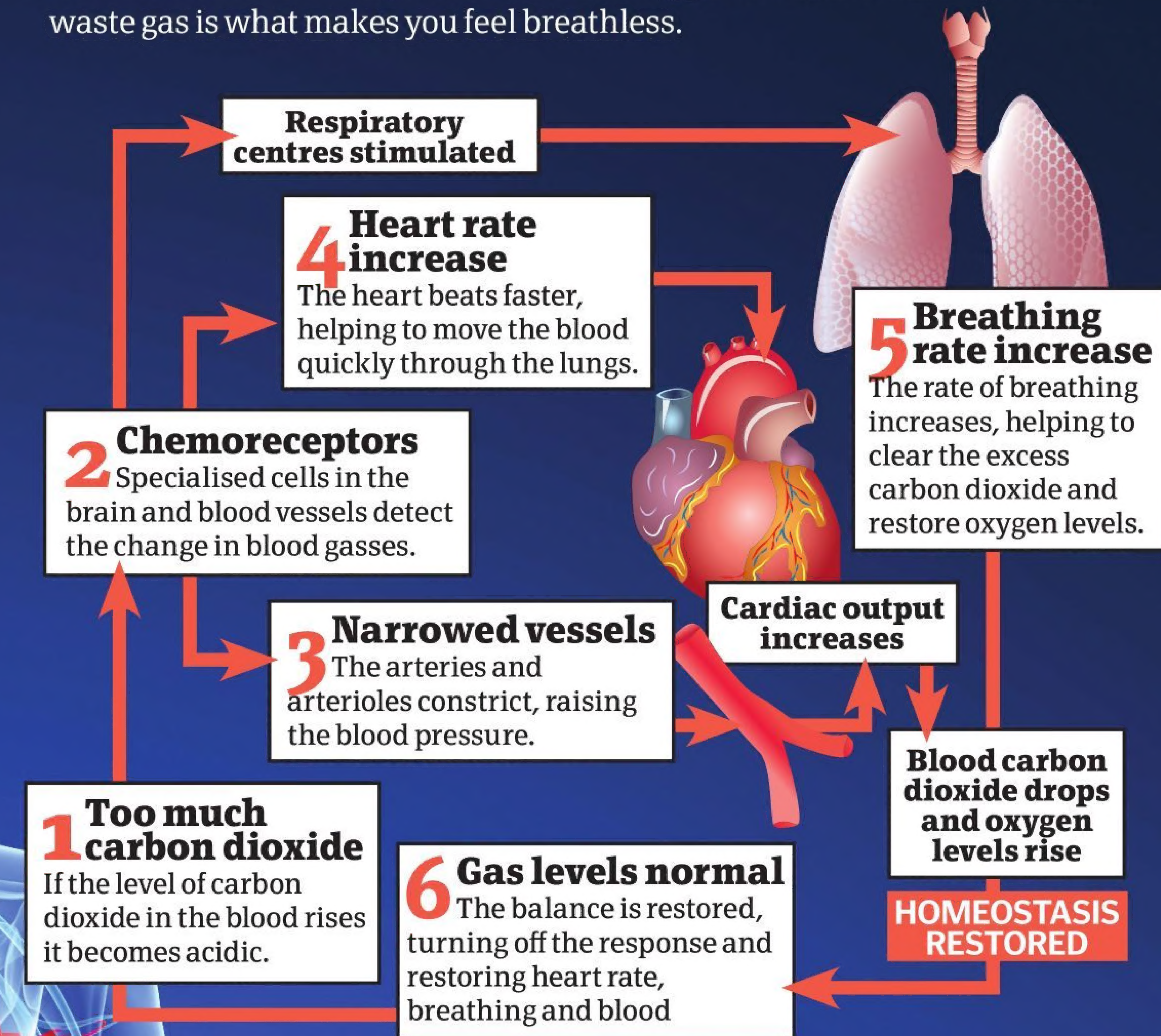
The ability to detect when we need to drink is crucial for survival. When we don't have enough water, the salts, sugars and proteins inside our bodies become more concentrated, and function starts to decline.

Minute changes in water level are detected by special cells in the brain called osmoreceptors, triggering the feeling of thirst. To prevent further water loss, the body releases a hormone known as vasopressin, which acts on the kidneys to stop water being excreted as urine. A hormone called angiotensin is also produced, making the blood vessels constrict and raising the blood pressure to compensate for the lack of water until more arrives.

Breathing

The ability to sense blood gases helps to keep oxygen and carbon dioxide levels normal

Breathing is controlled by the respiratory centres in the brain. Sensors in this area, along with sensors in the carotid artery and the aorta, detect the levels of gases in the blood and in the fluid that surrounds the brain. The carbon dioxide level is more important than the oxygen level, as a build up of this waste gas is what makes you feel breathless.

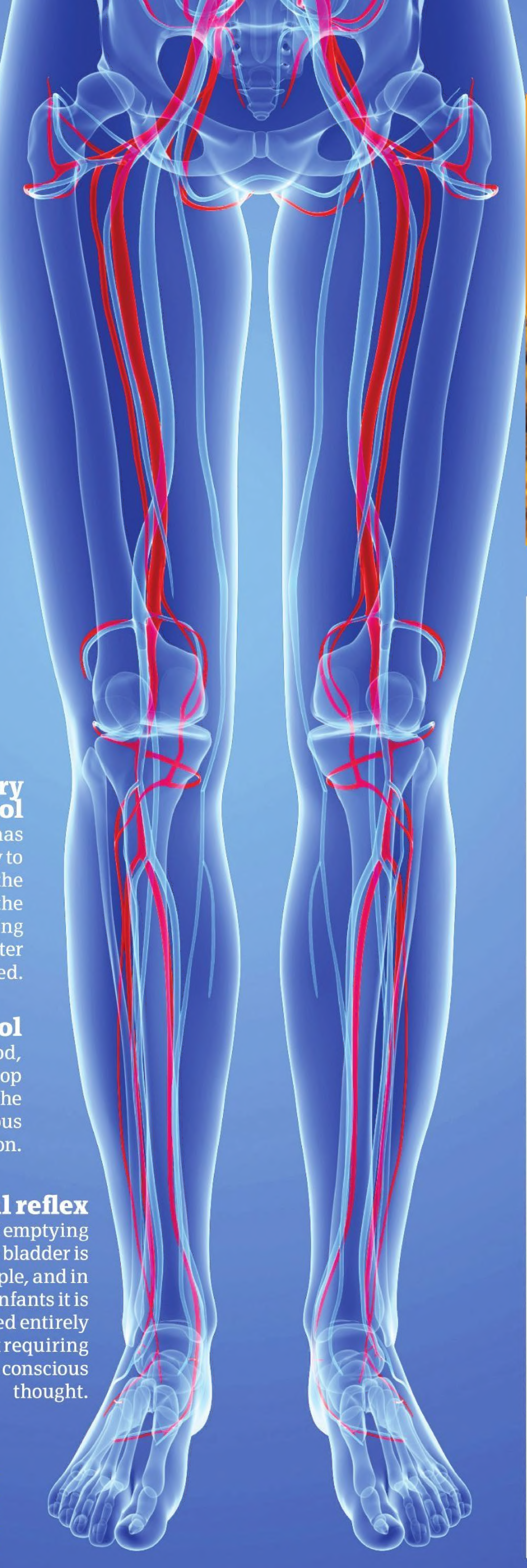


Hunger and fullness

Digestive sensors help to prevent us overeating, but they are easy to ignore

The feeling of hunger is controlled by a part of the brain called the hypothalamus. It produces two types of molecules: orexigens, which make you feel hungry; and anorexigens, which make you feel full. The hypothalamus decides which molecules to produce based on information sent by the digestive system.

When you haven't eaten for a while, the top part of the stomach starts to produce a molecule called ghrelin, signalling to the hypothalamus that you need to take in more food. After a meal, stretch receptors in your stomach help to signal that you are full, and when fat and protein start to enter the first part of the small intestine, a molecule called cholecystokinin (CCK) helps to switch the hungry feeling off.



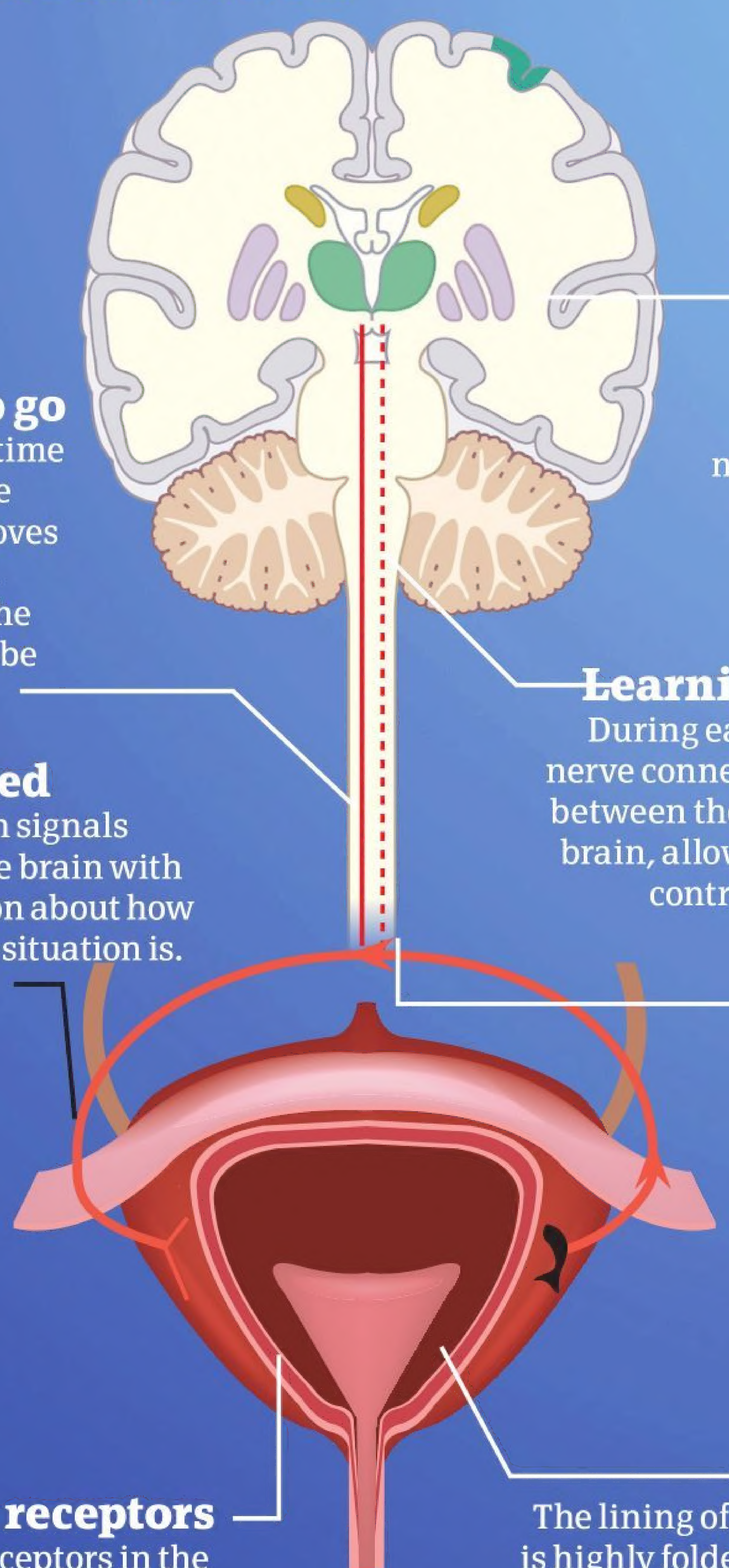
Excretion

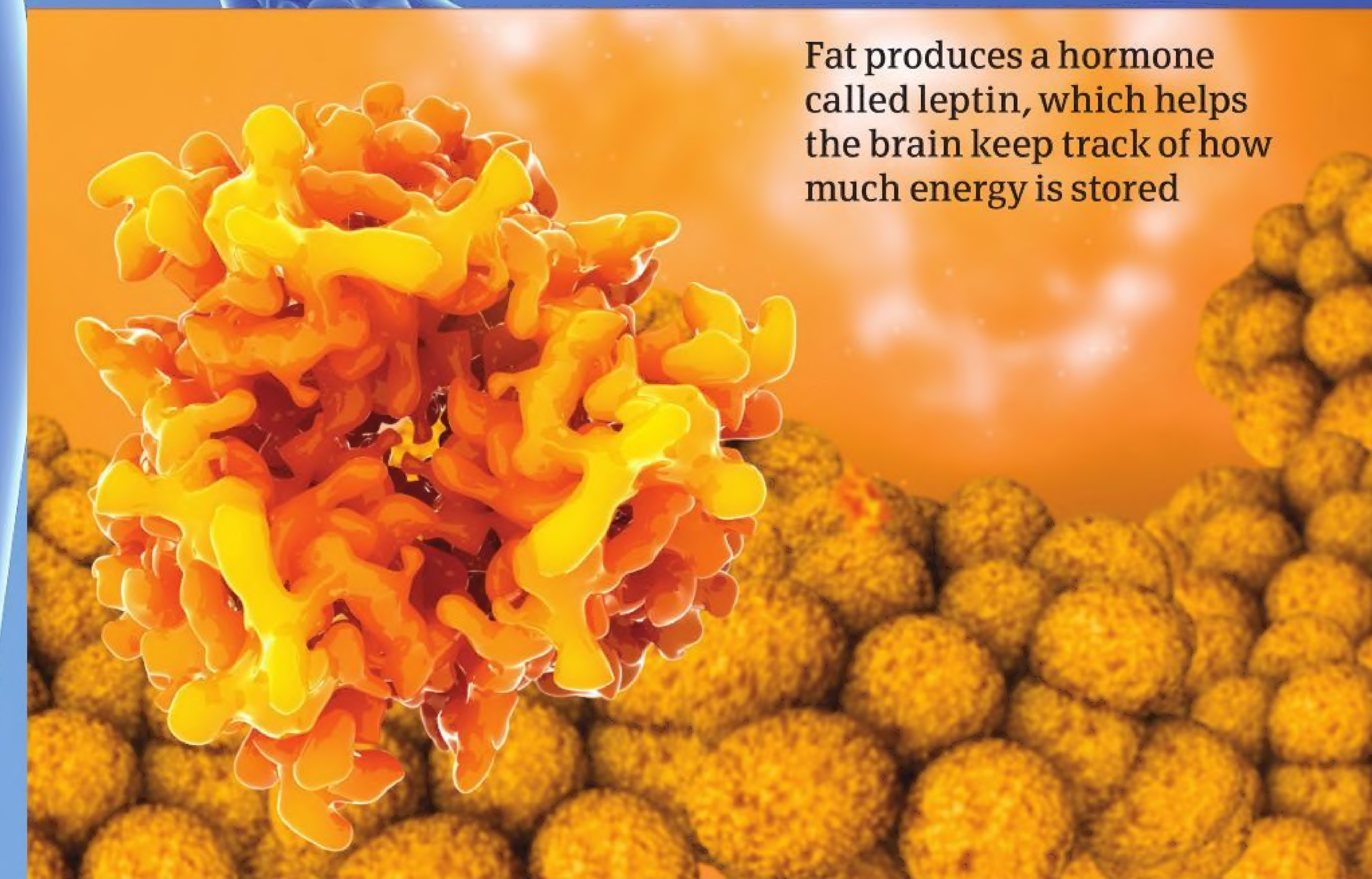
Internal sensors help to time the elimination of waste products from the body

It is vital to remove waste products from the body before they start to build up, and there are several internal systems responsible for sensing, processing, and removing waste. Some leave via the lungs, some via the back passage, and some via the bladder.

Control of waste disposal

Bladder emptying is timed using a specialised sense of touch





Fat produces a hormone called leptin, which helps the brain keep track of how much energy is stored

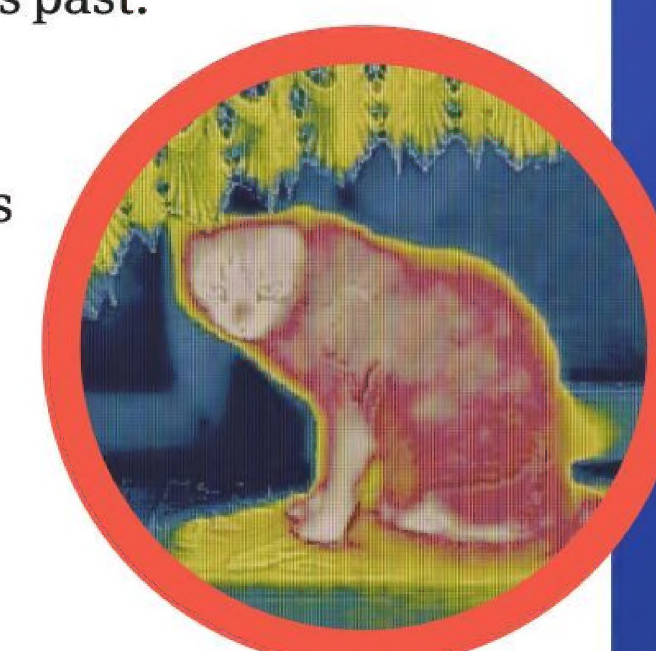
Animal senses

Magnetoreception

This incredible sense allows animals to detect Earth's magnetic field, and is shared by a diverse array of species, from honeybees to sea turtles. Birds may actually be able to see Earth's magnetic field lines by detecting the subtle changes that they make to the light, helping them to navigate in unfamiliar territory.

Electroreception

Muscle movements are powered by electrical impulses, and in water, dissolved ions can transmit the tiny currents. Many aquatic species are able to detect these subtle pulses, alerting them to danger or guiding them to their prey. Sharks, skates and rays have jelly-filled pores known as ampullae of Lorenzini, capable of detecting the slight differences in voltage as a fish swims past.



Heat vision

This specialised sense is used by pit vipers and some other snakes to detect the heat signature given off by their prey. Tiny pits on either side of the snake's head contain thousands of nerve endings that pick up infrared radiation, detecting changes in temperature of just fractions of a degree.

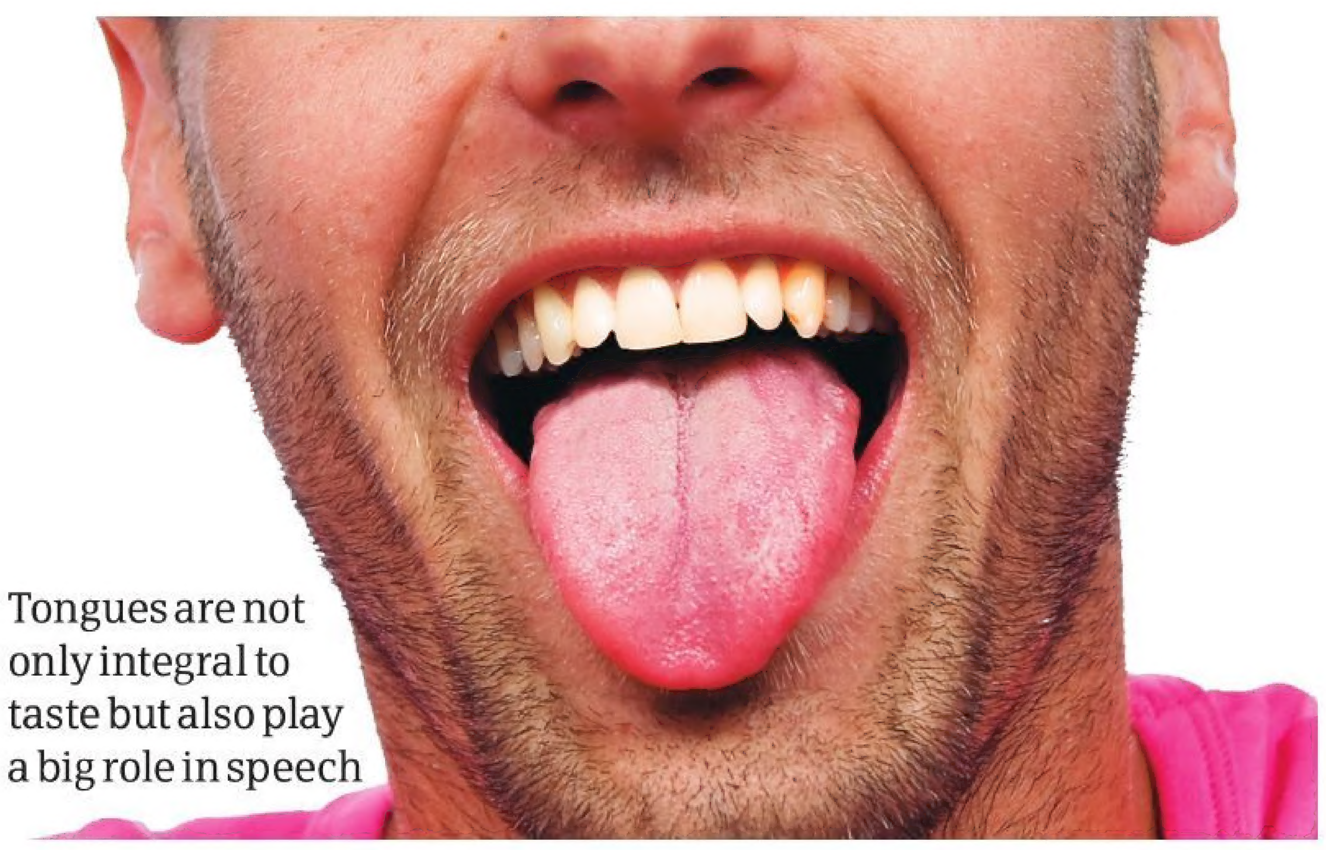
The human tongue

A versatile organ that allows you to both taste and talk

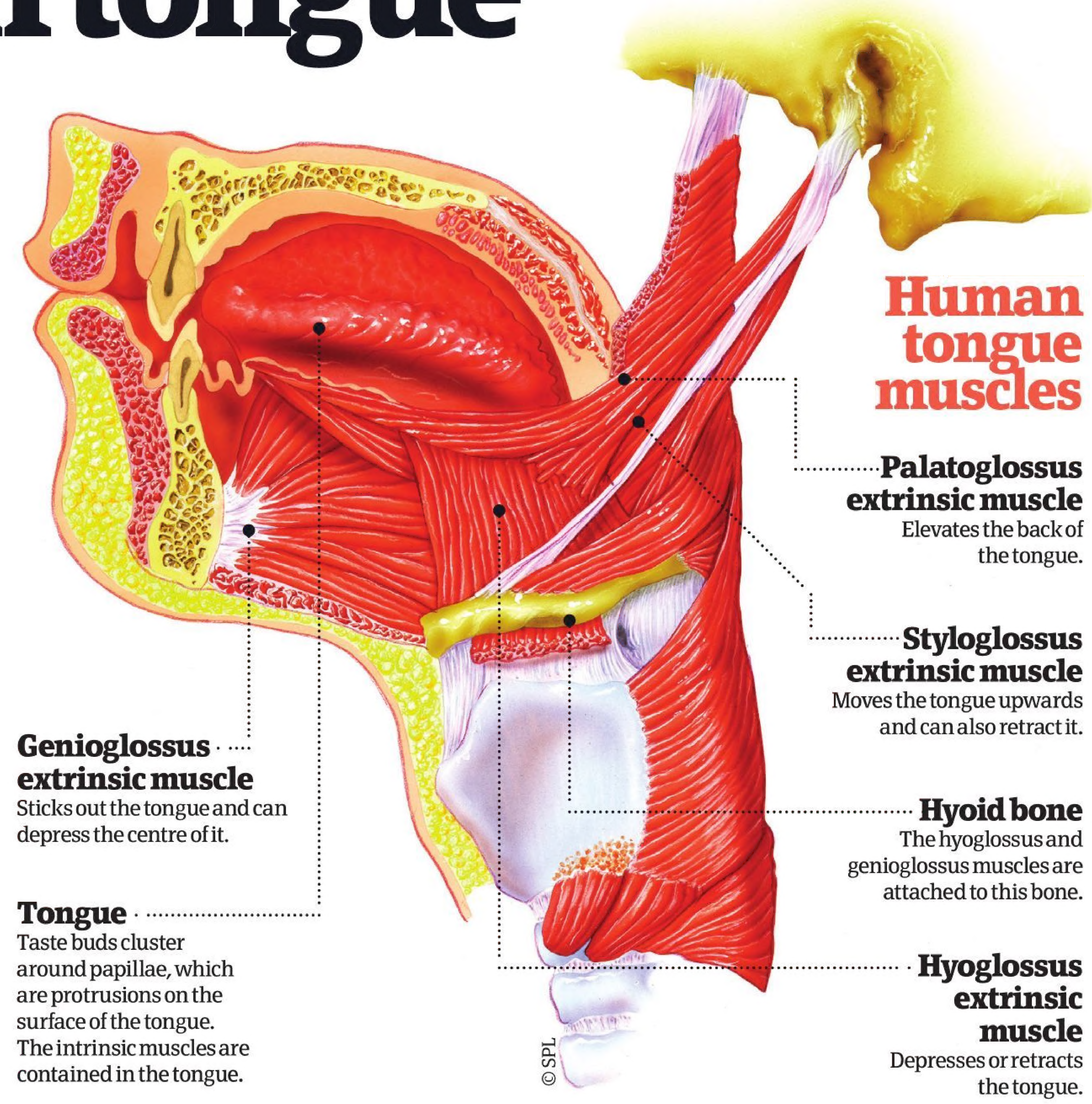
On our tongues, we have up to 10,000 taste buds that can distinguish between sweet, sour, bitter, salty and savoury flavours. As food is dissolved by our saliva, it meets taste receptor cells inside the taste buds that, when stimulated, send signals to the cerebral cortex. Receptors in the tongue also respond to other stimuli like pain, temperature and pressure.

The tongue consists of eight muscles: four of them are extrinsic muscles that are anchored to bone and change the position of the tongue, and four are intrinsic muscles that are not anchored to bone and change the shape of the organ.

Besides guiding food as we chew and swallow it, these muscles also give us the ability to speak. In combination with the mouth, jaws and cheeks the tongue moves to articulate sounds that emanate from the vocal folds of the larynx.



Tongues are not only integral to taste but also play a big role in speech



The five basic human tastes

Building a map of the tongue

There is general agreement that humans have five basic tastes, although the fifth taste 'primary' has only been recently officially recognised. Sweetness, bitterness, sourness and saltiness were joined by savouriness in 2002. Several other sensations that the tongue can recognise have been identified but are not classified as tastes.

Sweetness is associated primarily with simple carbohydrates – of which sugar is one of the most common. The way sweetness is detected is complex and only recently has the current model of multiple binding sites between the receptors and sweet substance itself been proposed and accepted. A sweet taste infers that the substance is high in energy and studies have shown that newborns in particular, who need a high calorie intake to grow, demonstrate a preference for sugar concentrations sweeter than lactose, which is found in breast milk.

Bitterness can be detected in very low levels and is generally perceived to be an unpleasant or sharp taste. Many toxic substances in nature are known to be bitter and there is an argument proposed by evolutionary scientists that bitterness sensitivity is an evolutionary defence mechanism. Humans, however, have now developed various techniques to make previous inedible bitter substances edible through reducing their toxicity, often through cooking.

The taste of saltiness is produced by the presence of sodium ions, or other closely related alkali metal ions. Potassium and lithium produce a similar taste as they are most closely related to sodium.

Sourness detects acidity. The way we measure the degree of sourness is through rating sour substances against dilute hydrochloric. The mechanism involved in detecting sourness is similar to saltiness in that taste is caused by a concentration of ions – in this case hydrogen ions. Savouriness is the newest of the recognised basic tastes and the taste is produced by fermented or aged foods. Glutamate is a common compound that can cause this taste and consequently savouriness is considered fundamental to Eastern cuisine.

Taste qualities are found in all areas of the tongue, although some regions are more sensitive than others

Your taste buds have very tiny, sensitive hairs called microvilli which send messages to your brain about how something tastes